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Human factors of posture entry into ergonomics analysis systems

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HUMAN FACTORS OF POSTURE ENTRY INTO ERGONOMICS ANALYSIS SYSTEMS

by

Douglas James Beck

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of the requirements of the degree of
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To my wife, Sheila

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LIST OF ABBREVIATIONS

3DSSPP	Three Dimensional Static Strength Prediction Program
C7	Disc 7 in the cervical region of the back (near base of neck)
GOMS	Technique for analyzing software without collecting empirical data (Goals, Operators, Methods, and Selection rules)
L5	Disc 5 in the lumbar region of the back (low back near tailbone)
NGOMSL	A Natural GOMS Language
S1	First disc in sacral region of the back (part of the tailbone)

CHAPTER I
INTRODUCTION

1.1 Thesis Statement

Working postures can be entered rapidly and accurately into ergonomics analysis systems using a human-computer interface that utilizes a behavior based inverse kinematics algorithm combined with direct manipulation. Such an interface requires less posture entry time and is more accurate than joint angle interfaces currently used in industry.

1.2 Research objectives

This dissertation investigates the effects of different types of human-computer interfaces on the entry of working postures into ergonomics analysis systems. Ergonomics analysis systems are used to assess the physical stress on workers and are typically implemented as computer software. For example, ergonomics analysis systems can be used to determine if lifting a 50 pound load as a part of a job increases the likelihood of a back injury over lifting a 25 pound load. Entering a posture means to describe the posture assumed by the worker in the detail required by the ergonomics analysis system. The most common method of entering postures into computer software is to type in the numerical values of the joint angles. Because the current posture entry methods are inefficient and inaccurate, this dissertation evaluates different posture entry methods to determine how future methods should be designed.

The operating hypothesis is that the use of an inverse kinematics algorithm for automatic posture prediction in combination with a direct manipulation interface will be significantly more efficient and accurate than the current methods of describing postures. To test the thesis statement, the following research objectives were established:

1. Review literature relating to the description of postures
2. Measure and photograph a number of working postures such that entered postures can be compared against actual postures
3. Verify the inadequacy of the current methods of entering postures
4. Develop an inverse kinematics algorithm based upon behavioral data
5. Design and implement three representative posture entry methods including a joint angle entry method, direct manipulation method, and a direct manipulation method that is combined with the inverse kinematics algorithm
6. Analyze the posture entry methods using the NGOMSL analysis technique to determine the differences between the methods
7. Test all three posture entry methods using novice users to determine the posture entry time, accuracy and training time
8. Test expert users of present joint angle entry methods to determine how practice has affected posture entry time and accuracy
9. Based upon statistical analysis of experimental data and the NGOMSL analysis, document the characteristics of the best posture entry method
10. Prepare written recommendations regarding posture entry methods and future research needs.

1.3 Research contribution

The effectiveness of software can be limited by the human-computer interface (Williges, Williges, and Elkerton, 1988). If users are unable to properly enter data into the computer, then the software is ineffective, even if the analysis portion is superb. This situation exists in ergonomics analysis software, such as the Three Dimensional Static Strength Prediction Program™ (3DSSPP) (Center for Ergonomics, 1990). While the analysis routines can effectively determine the injury potential of a job, entering postures into programs such as the 3DSSPP™ is inefficient and inaccurate. This causes

ergonomics analysts to be less inclined to use the software, even though there is no way to duplicate the analysis by other means.

An assumption made by this dissertation is that the anthropometric and postural data available to the analysts is minimal. This assumption is important because although detailed postural and anthropometric data can be obtained, expensive equipment and large amounts of time are required. Therefore, analysts are assumed to have only readily accessible data (worker height, worker weight, photographs and rough workplace dimensions). This means that the joint angles of working postures, such as Figure 1.1, cannot be easily obtained and must be estimated by the analyst. In addition, the link lengths are not known, and must be estimated using proportionality constants, such as Drillis and Contini (Chaffin and Andersson, 1991).



Figure 1.1 *An example of a job to be analyzed*

Research by Shepard and Cooper (1982) and Barfield, Sandford, and Foley (1988) determined that mental image rotation, a task similar to estimating joint angles from photographs, is difficult and time consuming. Therefore, the current posture entry methods are suspected to be quite difficult to use because most involve joint angle

estimation from non-orthogonal images of the posture. No previous research has collected empirical data on any posture entry methods, however.

While inverse kinematics algorithms that can predict posture automatically have existed in one form or another for many years (Kilpatrick, 1970), they have not been effectively integrated into human-computer interfaces for posture prediction. One reason for this is the accuracy of the inverse kinematics algorithms is suspected to be poorer than that which could be achieved by analysts entering the postures manually. Another reason is that sophisticated inverse kinematics algorithms also tend to be slow. However, no empirical tests have been performed either on the inverse kinematics algorithms or on the manual posture entry methods to determine their accuracy or the time required to use them.

While there are three phases in industry (design, prototype, and production) in which ergonomics analysis software can be used, the focus of this research will be on the production phase. The reason for this emphasis is because the accuracy of an entered posture at this phase is clearly defined, since the job already exists and actual postures can be measured to compare with entered postures.

Despite the focus on the production phase, the results of this research can be applied to any situation in which a posture is displayed on a computer screen and a user desires to change it. While inexpensive means of measuring working postures could make posture entry methods obsolete at the production phase, the design phase will still need ways to systematically and quickly alter postures. Some of the reasons that a user might have for changing a posture include prior experience with similar jobs, obstructions (such as machinery) in the workplace, unusual visual requirements to perform the job, or to determine the effects of a slightly different posture. The extreme variability of workstations and workers implies that a universal algorithm for predicting postures that will never need adjustments will be exceptionally difficult to develop. Therefore, good posture entry methods should be useful in the foreseeable future.

Accuracy at the production phase is a function of two factors; the ability of analysts to perceive the posture portrayed in a photograph and the ability of analysts to communicate their perceptions to the computer. While the perceptual ability of analysts does not vary between methods of entering postures, some methods can be significantly harder to use. This research is devoted to finding posture entry methods that analysts find easy to use, which will reflect better accuracy and less time required to enter a posture.

1.4 Dissertation organization

This dissertation is divided into eight chapters. Chapter I presents the objectives and the research contribution of this research. Chapter II reviews the literature related to the topic. Chapter III presents experiments which test current methods of describing postures. Chapter IV describes the development of a behavior based inverse kinematics algorithm. Chapter V describes the interfaces which were developed for this research. Chapter VI describes the research hypotheses and experimental design. Chapter VII describes an experiment which compares the performance of novices using three posture entry methods. Chapter VIII describes an experiment which evaluates the performance of experts using three posture entry methods. The conclusions and discussion of future research are in Chapter IX.

CHAPTER II
BACKGROUND

2.1 Overview

In order to reduce the number of injuries in industry, several computerized ergonomics analysis techniques have been developed (Chaffin and Andersson, 1991; Genaidy, Karwowski, and Mousavinezhad, 1990). These include static strength models, back compression models, and metabolic energy expenditure models (Beck, 1990). Computerized analysis software allows ergonomists to estimate the amount of stress on a worker's body based upon a general description of a job. The input data includes such information as the anthropometry of the worker, the postures assumed by the worker while performing the job, and the force exerted by the hands. In general, most of this information is easy to enter into ergonomics analysis software. However, posture can be more difficult to enter because of the spatial complexity of the human body (Keyserling and Budnick, 1987) and the limitations of visual perception (Wickens, 1984).

Since entering postures into ergonomics software is difficult, then posture entry is a key issue in the design of an effective user interface. The ease of use of a computer system is critical to user acceptance (Williges, Williges, and Elkerton, 1988). Thus, this research is focused on the human factors of a computerized posture entry system.

2.1.1 Posture entry : A critical ergonomics analysis problem

Ergonomics analysis requires accurate postures to be entered in order to yield accurate biomechanical results. One of the common techniques for describing a posture, particularly for static strength and back compression models, is to enter joint angles. The number of joint angles that need to be specified are quite numerous. The 3DSSPP™, a common ergonomics analysis program, uses 15 joint angles to describe a posture (Center for Ergonomics, 1990). This makes posture entry difficult and time consuming although no research has been performed to verify how much time is required for users to enter a posture using this method. The accuracy that can be attained is also unknown. Research by Chaffin and Erig (1991) determined that small changes in posture (10 degrees at a single joint) can make a significant (up to 30%) difference in the resulting human strength predictions. Thus, accurate posture entry is an essential part of any system that performs ergonomics analysis.

Despite the importance of accurate postures, analysts desire spend as little time as possible collecting workplace data. This means that joint angles generally cannot be measured (see section 2.3.3) nor can specific anthropometric data (such as link lengths) be measured. Because of this limitation, analysts must rely on postural and anthropometric approximations. The posture data is estimated from a photograph or videotape, and the anthropometric data is estimated based upon the height and weight of the worker using proportionality constants such as Drillis and Contini (Chaffin and Andersson, 1991).

2.1.2 Posture entry: A complex human perception problem

One particular psychological phenomenon that is significant to posture entry is mental image rotation. Mental image rotation is the ability of humans to rotate a three

dimensional shape in their minds. This skill is often required in posture entry because users must convert what is presented (i.e. a picture of a worker) into 3D data required by the computer for the analysis (i.e. joint angles). Unfortunately, there is no analytical means to determine if mental image rotation is definitely occuring. However, mental image rotation research does point out the complexity of dealing with three dimensional shapes, like the human body, from a psychological standpoint.

The basic experimental procedure of mental image rotation, originally used by Metzler and Shepard (1974), involved showing subjects a three dimensional object to memorize. Next, another 3D object was shown which was either a completely different object or the same object rotated about one of the axes. The subject then responded whether or not the two objects were the "same" or "different". The result of this experiment, which has been duplicated numerous times, is that the time to respond is linearly related to the amount of rotation. In other words, the more an object is rotated, the more time was required for subjects to identify the object. Metzler and Shepard reported a slope of about 60 degrees per second, with an intercept of one second. Therefore, a 180 degree mental image rotation would take about 4 seconds.

Whenever a subject made an incorrect response of "same" or "different", this was considered an error. The error rate reported by Shepard and Metzler was quite low, about 3%. The error rate became much higher in research performed by Rock, Di Vita, and Barbeito (1981) when subjects were not given sufficient time to perform the mental image rotation. Additional research performed on complex versus simple objects (Barfield, Sandford, and Foley, 1988) demonstrated that the time to mentally rotate a complex object was 2 to 3 times higher than for a simple one. Carpenter and Just (1978) found that mental image rotation was accompanied by a series of eye fixations on the critical details of the object to be rotated. The more complex the object, the more eye fixations required, and

therefore the more time that is required. Hence, mentally rotating the entire human body, which is a complex linkage, is probably quite time consuming.

2.1.3 Criteria for a good posture entry system

In order to be able to evaluate different posture entry methods, the first task is to identify the features of a good method for entering postures. First of all, a posture entry method must be accurate. Accuracy is defined as how close the entered posture is to the actual posture. This can be measured as the difference between the entered and actual joint angles.

A second important criteria is the amount of time required to use a posture entry method (Launis and Lehtela, 1990). If a method is tedious, then ergonomists will be less willing to use it or will not take the time to choose accurate postures. Real world computer systems cannot be designed without considering the amount of time to use the software. Furthermore, fast entry of postures allows additional types of analyses to be used more effectively, such as upper extremity posture analysis and dynamic biomechanical analysis. These analyses depend on multiple postures to be entered.

The decision that a posture is satisfactory is affected by the emphasis that the user places on accuracy. In order to make the concept of posture entry time more concrete, an assumption for the purposes of this research is that high emphasis is placed on accuracy. Since postures have a significant effect on ergonomics analysis, ergonomists must place high emphasis on accuracy. Without this assumption, posture entry time is not meaningful since any method can be extremely fast if accuracy is not considered.

2.1.4 Definition of posture

A convenient method for describing posture is by the use of joint angles. (Priel, 1974; Chaffin and Andersson, 1991; Center for Ergonomics, 1990) Joint angles are usually defined with respect to the horizontal and vertical planes. The origin of the coordinate system is considered to be the point on the floor beneath the midpoint of the ankles. Thus, if the feet remain planted, then the direction of positive horizontal angles is in front of the body, with negative angles behind. The combination of a horizontal angle with a vertical angle defines a three dimensional point in space. Joints that do not have three degrees of freedom can be described by a single angle.

The most difficult parts of the body to describe are the arms, because the shoulder, elbow and hand form a two joint system. Each of the two joints is described by a horizontal and a vertical angle, see Figure 2.1. For a more complete description of the arm and shoulder angles, see Hsiao and Keyserling (1991). The complexity of describing the arms means that if a user desires to move a hand to a certain location, then there are multiple postures that could be selected even with a fixed shoulder position. In other words, given a hand location and a shoulder location, there is not necessarily a single location for the elbow. The user often must make a decision for the position of the elbow, which can have a significant influence on ergonomics analysis because human strength varies throughout the range of motion (Chaffin and Andersson, 1991). The elbow and shoulder strengths were most often found to limit force production (Chaffin and Erig, 1991), thus making correct postures critical for these joints.

The trunk is a second portion of the body which also has three degrees of freedom. The position of the trunk can be critical because of the impact that the heavy mass of the upper body can have on an ergonomics analysis. The three degrees of freedom are defined by the trunk flexion angle, lateral bending angle, and axial rotation angle. (See Figure 2.2)

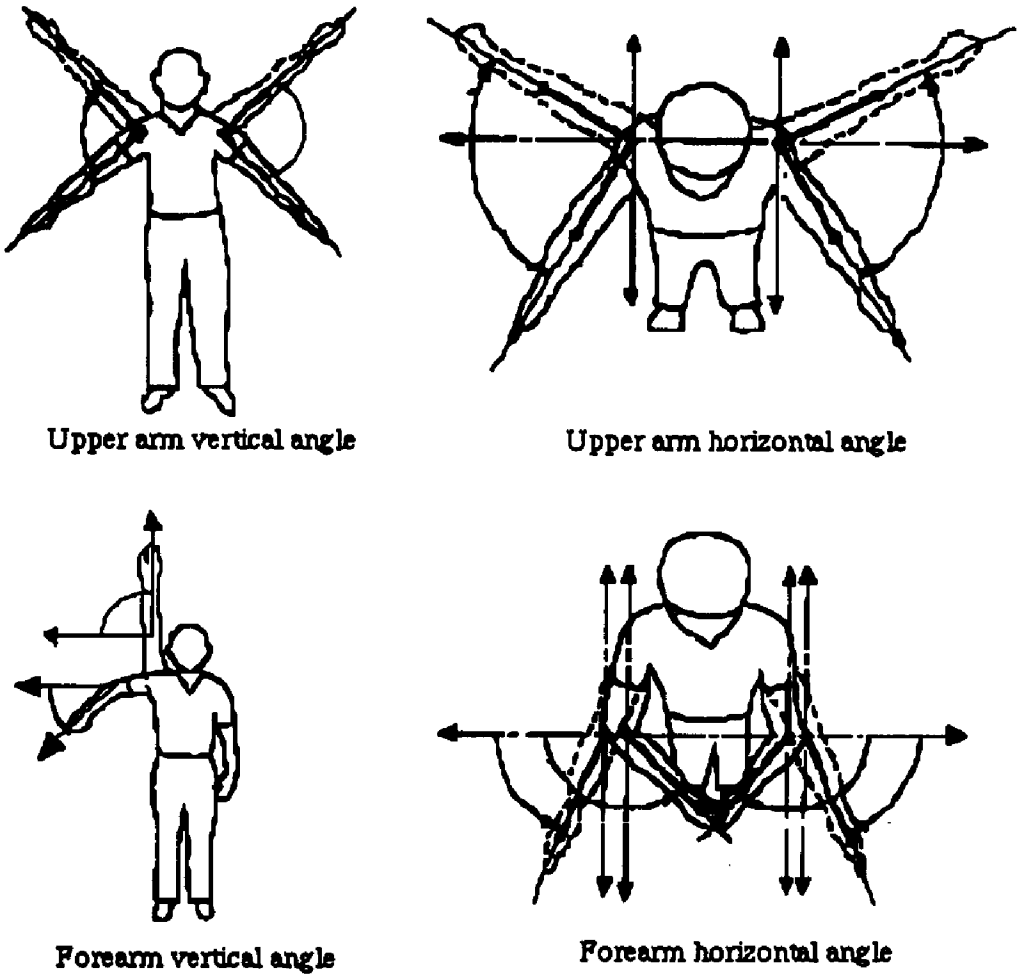


Figure 2.1 *Upper arm and forearm joint angles*

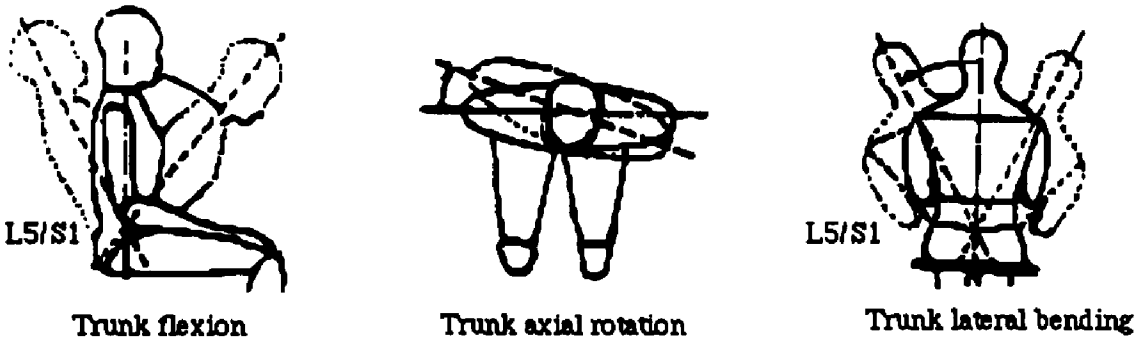
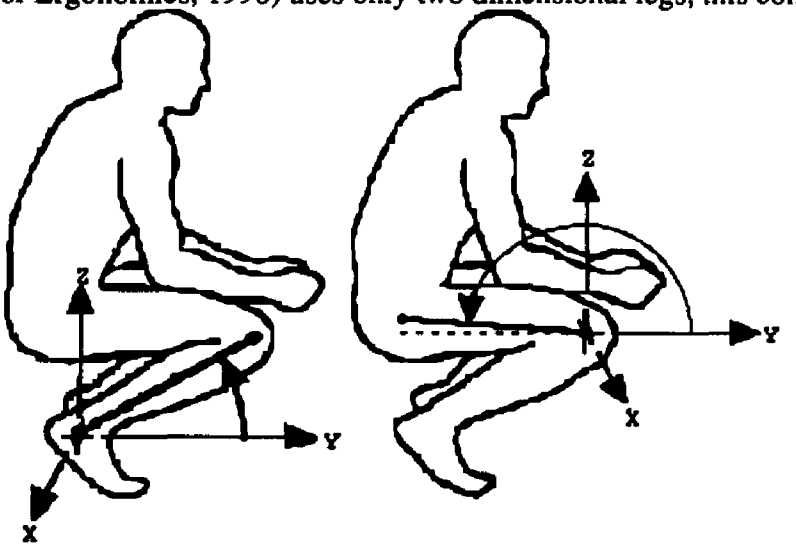


Figure 2.2 *Trunk posture definitions*

While the legs actually have three degrees of freedom like the arms, they can be approximated by a two degree of freedom system as shown in Figure 2.3. Therefore, the legs are quite easy to enter properly in those kinematic systems that use only two dimensional legs. Because a common ergonomics analysis model, the 3DSSPP™ (Center for Ergonomics, 1990) uses only two dimensional legs, this convention was followed.



Lower leg vertical angle **Upper leg vertical angle**

Figure 2.3 *Leg angle definitions*

2.1.5 Data available to the user

Ergonomics analysis programs are used at multiple phases of the industrial design/implementation process. The first stage where ergonomics analysis could be used is in the preliminary design stage. At this stage a user may not have any specific workplace data, only general characteristics, such as a workstation sketch. Ergonomics analysis will yield approximate results which can be used to compare different proposed workstation designs. The user will not have any joint angles available, and therefore they must be estimated. In general, the postures entered at this stage cannot be precise.

Another phase in which an ergonomic analysis could be used is the prototyping stage. At this point the job can be simulated, (at high expense), so all of the workplace data can be determined. Joint angles can be obtained experimentally by the use of goniometers, flexometers, or photogrammetry. (Chaffin and Anderson, 1991). Therefore, at this stage the user can enter posture data quite easily because the joint angles have been measured directly.

The third phase takes place during production when the job is actually being performed. All of the workplace data is available, but the posture must be estimated from a videotape or photograph. Generally, the workplace will not allow joint angles to be obtained experimentally. This means that the measured joint angles, similar to the design stage, are not available.

2.1.6 Applications of posture entry to fields other than ergonomics

While the primary focus of this research is the study of posture entry methods for ergonomics software, there are applications in other fields such as choreography and film making. While these fields do not require the same posture accuracy as ergonomics, the large number of postures to be entered requires that the posture entry method be efficient.

Posture entry is an issue in choreography because of the need to document dance postures. Traditionally, dances were documented using complicated notations (Benesh and Benesh, 1956; Laban, 1971; Hutchinson, 1977) which require a large amount of training time to master. More recently, computerized methods of describing dance postures have been developed in order to reduce the amount of training (Schiphorst, Calvert, Lee, Welman, and Gaudet, 1990). COMPOSE, a choreography program, is discussed in more detail in Section 2.2.2.

Computers have been used to aid film makers since the late 1960's. (Goodman, 1987). While the early use of computers focused on a few special effects, more recent

films such as *Young Sherlock Holmes* and *Tron* have included animated humans. JACK (Lee, Phillips, Otani, and Badler, 1990), an interactive graphic human model developed at the University of Pennsylvania, has been used in the production of a music video. The posture entry methods used by JACK are discussed in Sections 2.2.2 and 2.3.2.

2.2 CURRENT SEGMENTAL METHODS FOR ENTERING POSTURES

This section summarizes the different segmental methods which can be used to enter working postures. A segmental method is a posture entry method which positions the individual body segments one at a time. Segmental methods are more commonly used than whole-body methods, which are described in Section 2.3. The segmental methods currently used in industry are summarized in Table 2.1.

TABLE 2.1 *Segmental posture entry methods*

Method	References
Labanotation	Laban (1971) Hutchinson (1977)
Benesh Dance Notation	Benesh and Benesh (1956) Kember (1976)
Posturegram	Priel (1974)
Posture recording	Cote Gil and Tunes (1989)
OWAS	Karhu, Kansi, and Kurinka (1977) Karhu, Harkonen, Sorvalli, and Vepsalainen (1979) Kivi and Mattila (1991)
Upper extremity posture recording	Armstrong, Foulke, Joseph, and Goldstein (1982) Armstrong (1986)
Postural Analysis System	Keyserling (1986a) Keyserling (1986b)
Posture targetting	Corlett, Madeley, and Manica (1979)
Keyboard joint angle method	Center for Ergonomics (1990)
Angle definition menu	Beck (1990)
Joint angle wheel	Philips, Zhao and Badler (1990)
Spherical angle method	Schiphorst, Calvert, Lee, Welman, and Gaudet (1990)

2.2.1 Categorical methods

The basic way to use categorical methods is to select the desired posture from among several different predefined categories of postures. Typically, this selection procedure is repeated for different parts of the body, such as the arms, legs and trunk, to yield a whole body posture. Because the posture entry method is simple, the only equipment required to record a posture is a pencil and a coding form. Examples of categorical methods are Labanotation, Benesh Dance Notation , the Posturegram Posture recording, OWAS, Upper Extremity Postural Analysis and the Postural Analysis System. Examples of each method are shown in Figures 2.4 through 2.10.

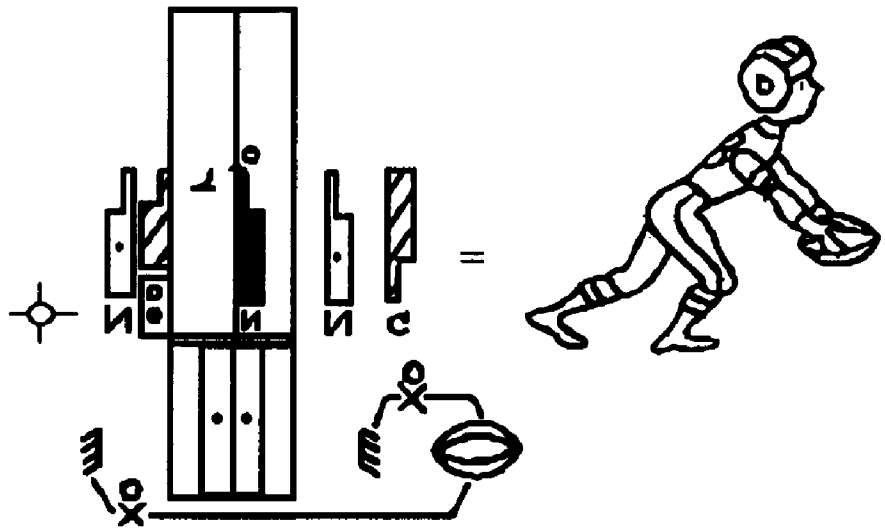


Figure 2.4 *Labanotation description of a football player's posture (from Hutchinson, 1977)*

POSTUREGRAM — Serial number _____

Company's name: _____
Department: _____
Task/Operation: _____
Operator(s): _____
Analyst: _____ Checked by: _____
Date recorded: _____ Issued on: _____
Reviewed on: _____
Reason: _____

Sketch:

Circle appropriate indications

Reference plane	Inclined towards	Approximate angles
BODY'S FRONTAL PLANE	R.N. / L.N.	0 5 10 20 30 45 60 75 90°
BODY'S LATERAL PLANE	Front / Back	0 5 10 20 30 45 60 75 90°

LEFT-HAND SIDE		RIGHT-HAND SIDE
Located at level number above (+) or below (-)	Levels of joints at "zero position"	Located at level number above (+) or below (-)
+ - 1 2 3 4 5 6 7 8 9 0	9 Above head 9	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	8 Neck 8	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	7 Shoulder 7	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	6 Elbow 6	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	5 Wrist 5	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	4 Hips 4	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	3 Knees 3	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	2 Ankles 2	+ - 1 2 3 4 5 6 7 8 9 0
+ - 1 2 3 4 5 6 7 8 9 0	1 Toes 1	+ - 1 2 3 4 5 6 7 8 9 0

Record angle and direction + or -

In reference plane			Direction + or - and angle of inclination of limbs	In reference plane		
Frontal	Lateral	Horizontal		Frontal	Lateral	Horizontal
____	____	____	Head	____	____	____
____	____	____	Shoulders	____	____	____
____	____	____	Arms	____	____	____
____	____	____	Forearms	____	____	____
____	____	____	Hands	____	____	____
____	____	____	Trunk	____	____	____
____	____	____	Thighs	____	____	____
____	____	____	Legs	____	____	____
____	____	____	Feet	____	____	____

Brief verbal description of the posture: _____

Figure 2.5 *Posturegram coding form (from Priel, 1974)*

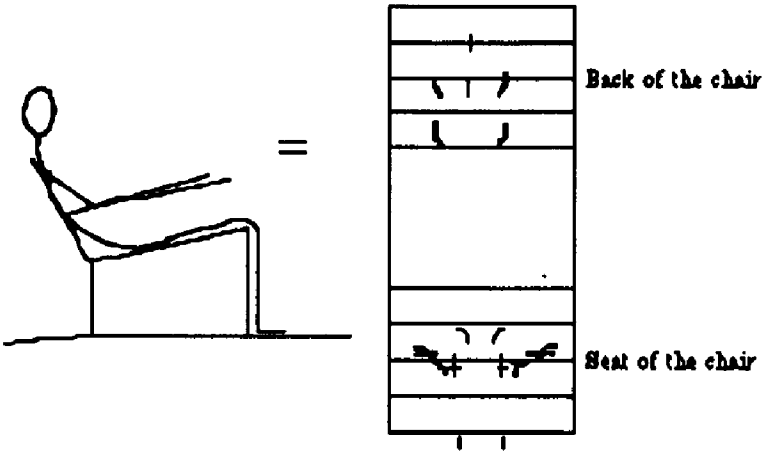


Figure 2.6 *Benesh Notation description of a seated posture (from Kember, 1976)*

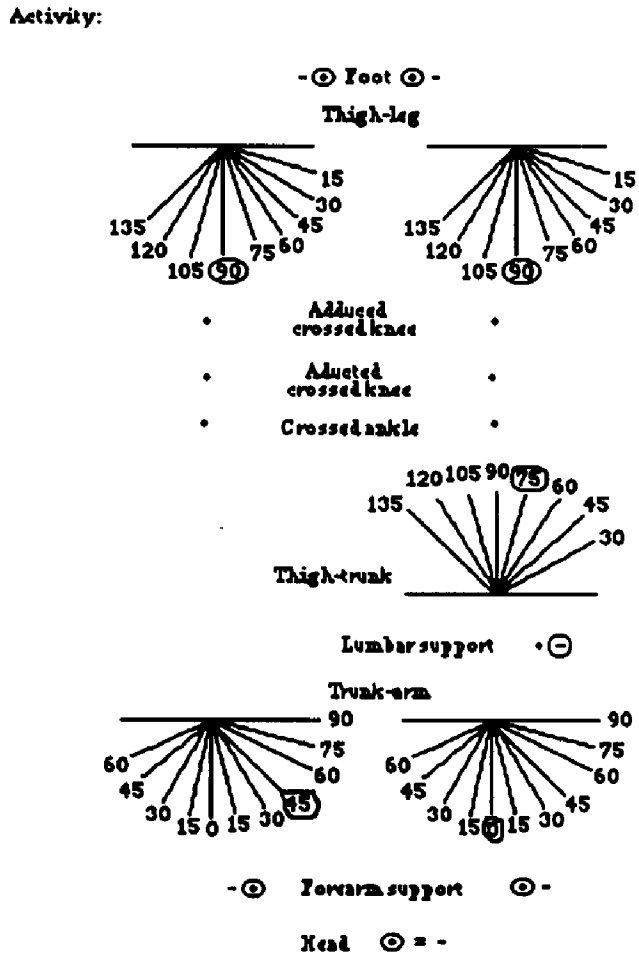


Figure 2.7 *Posture recording (from Cote Gil and Tunes, 1989)*

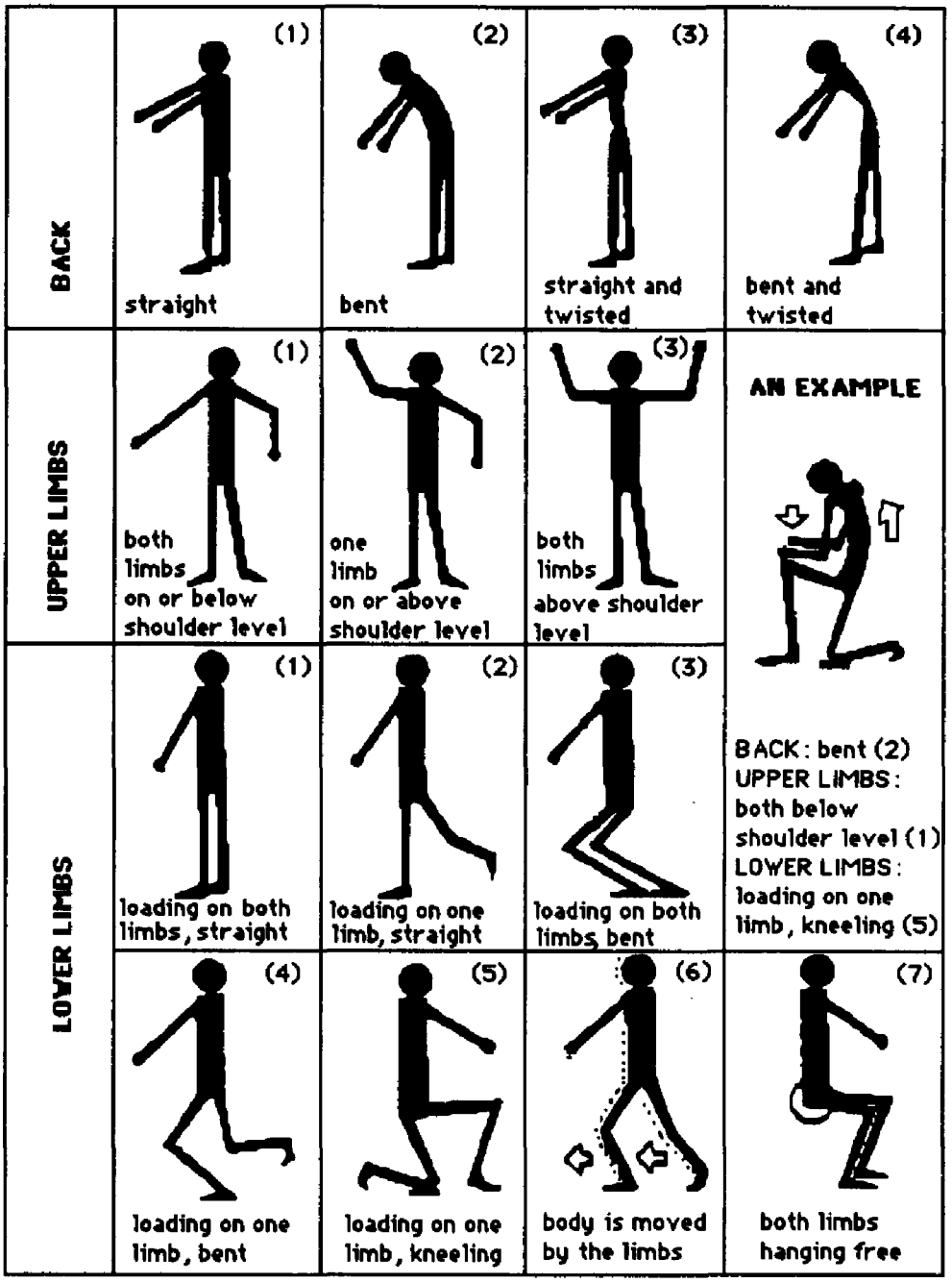


Figure 2.8 *OWAS posture categories (from Karhu, Kansi, and Kurinka, 1977)*

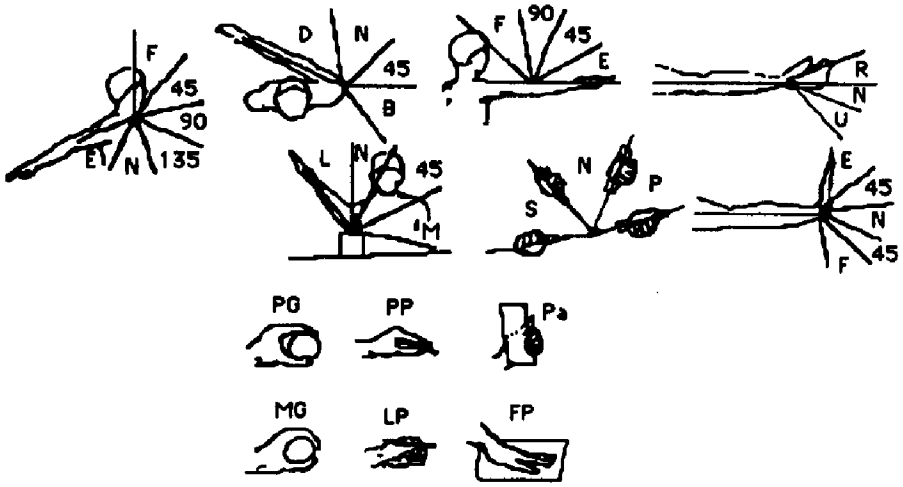


Figure 2.9 *Upper extremity postural analysis (Armstrong, 1986)*

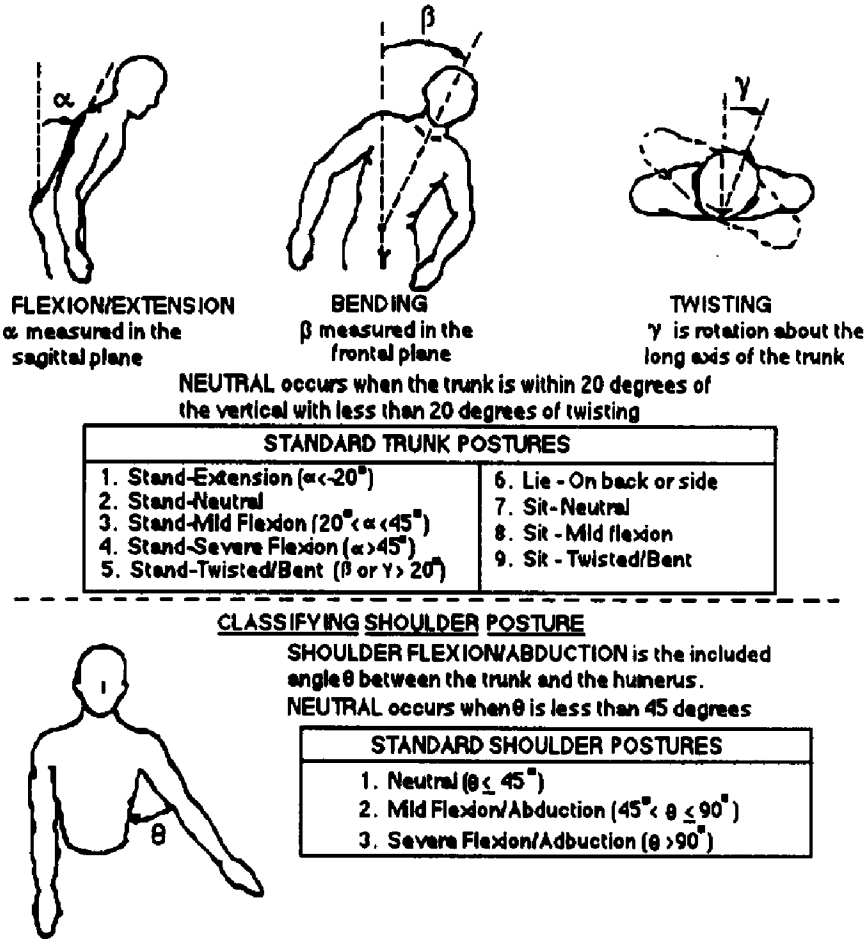
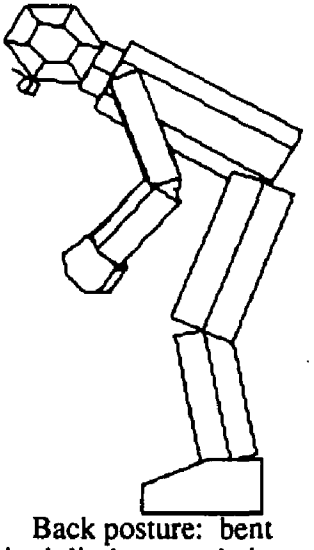


Figure 2.10 *Postural Analysis System categories (Keyserling, 1986a)*

For example, when using the OWAS system (Figure 2.8), the analyst must select a category for the back, upper limbs and lower limbs. There are four back categories, three upper limb categories and seven lower limb categories. Figure 2.11 shows a posture which has been described using OWAS. Notice that a wide range of postures would be described using the exact same categories. Each category corresponds to range of at least 30 degrees. This means that there is no way to describe postures to the accuracy recommended by Chaffin and Erig (1991).



Back posture: bent
Upper limbs: both limbs on or below shoulder level
Lower limbs: loading on both legs, straight

Figure 2.11 *OWAS description of a working posture*

2.2.2 Joint angle posture entry methods

Joint angle posture entry methods allow the user to specify the angle of each of the major joints in the body. Because of the complexity of entering joint angles, joint angle methods are usually implemented as computer software which provides feedback in the

form of stick figures or a three dimensional graphic human model. Joint angle posture entry methods are the most commonly used posture entry methods in industry today.

One joint angle posture entry method is known as posture targetting (Corlett, Madeley, and Manenica, 1979), which is shown in Figure 2.12. Dots are marked on targets representing the angle of each limb with respect to a neutral posture. For example, to specify that a limb is at an angle of 45° to the left of neutral, a dot is placed on the target 45° to the left of the center. The distance from the origin represents how far that joint is flexed or extended away from neutral. The joint angles can then be calculated by digitizing the positions of the dots.

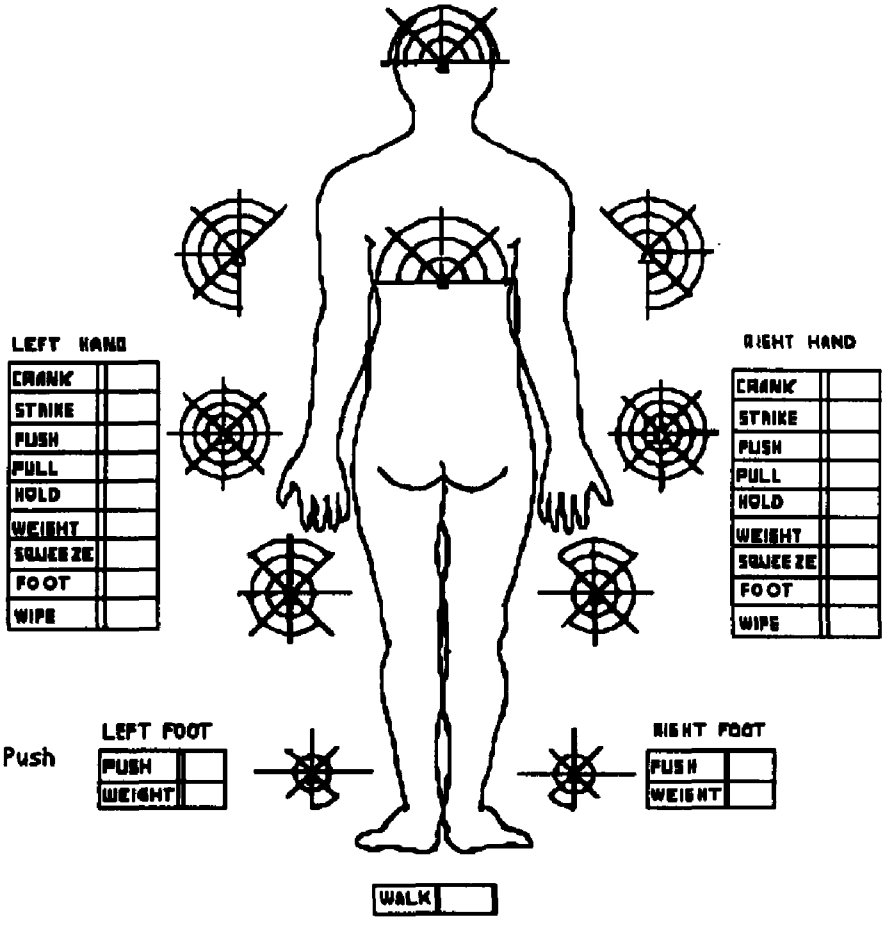


Figure 2.12 *Posture targetting (Corlett, Madeley, and Manenica, 1979)*

For example, the trunk posture of the worker shown in Figure 2.13 is described using Posture Targetting. Notice that since the worker is bending to the right, the point on the target is also to the right. Since the worker is bending forward moderately, the dot is in between the first and second arcs away from the center.

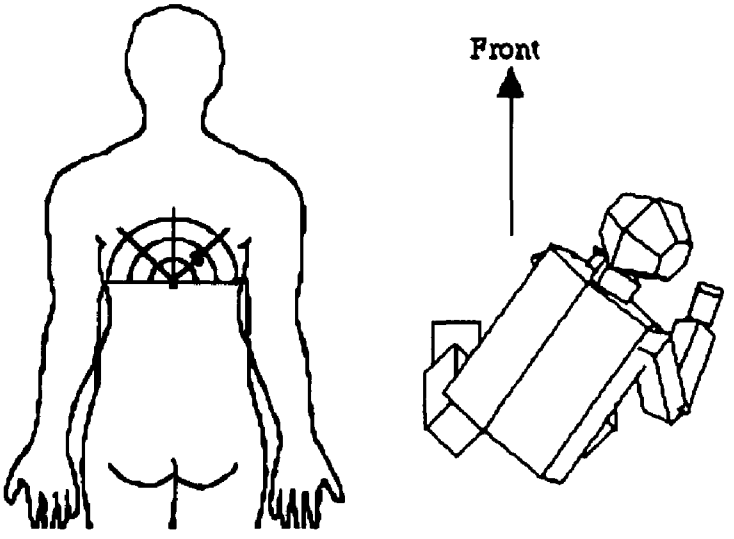


Figure 2.13 *Description of a trunk posture using posture targetting*

Another approach is to directly specify the joint angles of the desired posture (relative to the horizontal and vertical planes) by typing them in, as shown in Figure 2.14. This method is used by the 3DSSPP™. A variation on this method is to use an angle definition menu (Beck, 1990), as shown in Figure 2.15. The user selects a desired joint angle from the angle definition menu by using a mouse. However, similar to the other joint angle entry methods, only one angle can be manipulated at a time. This can become complicated for the trunk and the arms because of the three degrees of freedom.

Rt Lower Leg Vert:	80
Rt Upper Leg Vert:	135
Rt Upper Arm Vert:	-90
Rt Upper Arm Horz:	90
Rt Forearm Vert:	-80
Rt Forearm Horz:	90
Lt Lower Leg Vert:	-80
Lt Upper Leg Vert:	90
Lt Upper Arm Vert:	80
Lt Upper Arm Horz:	135
Lt Forearm Vert:	-90
Lt Forearm Horz:	90
Trunk Flexion:	20
Trunk Rot Axial:	0
Trunk Lateral Bend:	0
Rt Hand Force Vert:	-90
Rt Hand Force Horz:	90
Lt Hand Force Vert:	-90
Lt Hand Force Horz:	90

Figure 2.14 *Angle entry menu from 3DSSPP™*

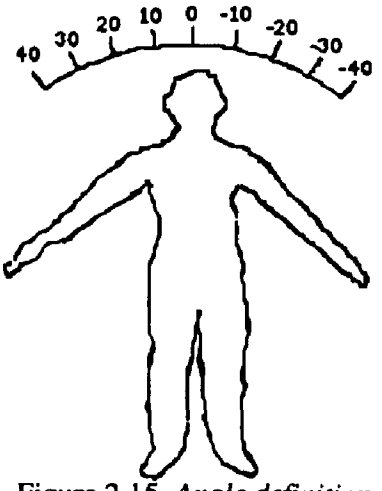


Figure 2.15 *Angle definition menu*

The joint angle wheel (Figure 2.16) is another method of specifying joint angles (Philips, Zhao, and Badler, 1990) Users select the appropriate angle for the joint on the wheel using a pointing device. The advantage of using a joint angle wheel is that the joint angle definitions are easier to understand.

An alternative approach to entering angles relative to the horizontal and vertical planes is to use spherical angles. In the spherical angle entry method, the user selects the desired body part and then enters the orientation of that part on a sphere. In essence, the joint angles are entered as spherical coordinates. However, the spherical coordinates are entered by selecting a position on a sphere using a pointing device, so the user does not have to actually calculate the spherical coordinates. An example of this method is shown in Figure 2.17. The near and far half spheres are used to enter the spherical coordinates. The far sphere is behind the body and the near sphere is in front. This method is currently used by COMPOSE™, a choreography program (Schiphorst, Calvert, Lee, Welman, and Gaudet, 1990).

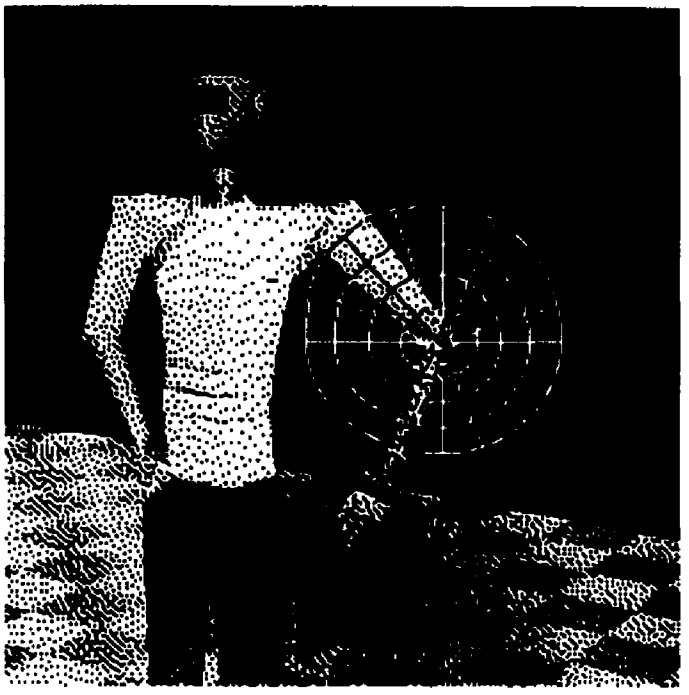


Figure 2.16 *JACK and the joint angle wheel (Courtesy of N. Badler)*

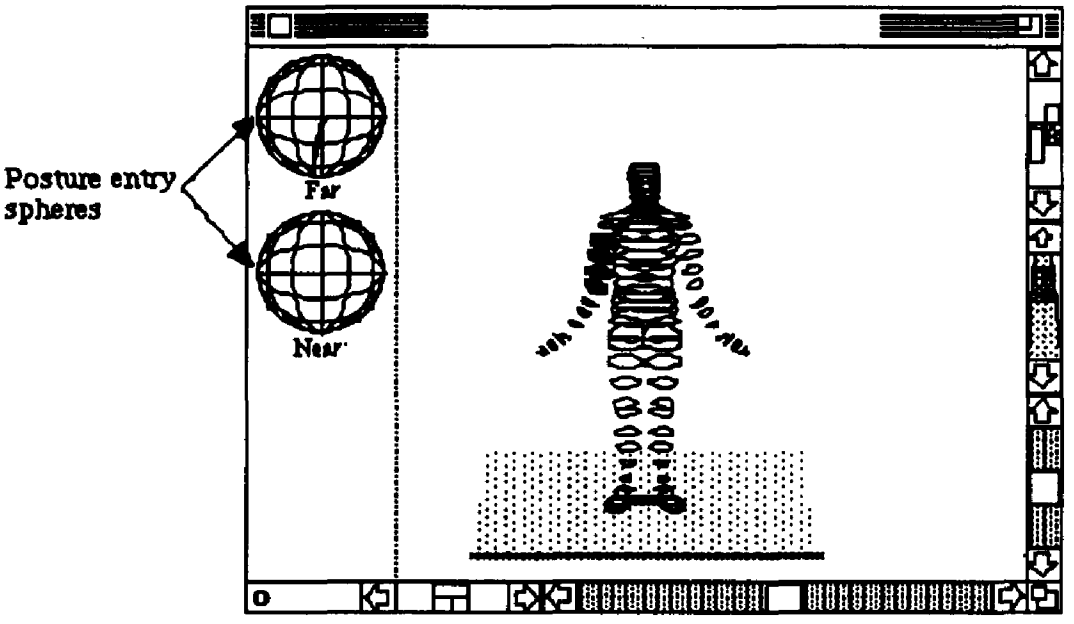


Figure 2.17 *Spherical angle posture entry method (from COMPOSE™)*

2.3 Current whole-body posture entry methods

Several posture entry methods exist which allow users to enter whole-body postures as opposed to entering single body segments one at a time. This section describes three classes of whole-body posture entry methods

2.3.1 Three dimensional digitization method

This method involves the use of an external three dimensional manikin which the users can manipulate into the desired posture. Once the desired posture has been attained, the users can digitize each of the joint positions using a three dimensional digitizing wand and store the data on a computer. This method was implemented by Keyserling and Budnick (1987). They reported an average of three minutes to enter a posture using this technique. The main drawback to this method is that it requires reading in the postures using external equipment which can be expensive and complicated to set up. Furthermore, because only surface coordinates of the joints can be digitized (and not the joint centers of rotation), the accuracy of this method is limited.

2.3.2 Inverse kinematics algorithms

All of the posture entry methods described earlier require that the user determine the posture without any aid. The computer simply displayed the individual body segment postures which had been entered and did not aid the user by pre-positioning the whole-body for a task. The idea behind inverse kinematics is that there are means for estimating segmental postures, assuming that a general description of the whole-body posture is available. Data that are often available to describe a whole-body posture are anthropometry and a workstation sketch. Hand locations can be estimated from the workstation sketch.

The use of inverse kinematics algorithms relieves the user of some of the burden of entering individual body segment postures.

Several different approaches have been taken to perform inverse kinematics. One method is to find the optimal whole-body posture based upon minimizing the forces on the body (Lee, 1988; Zhao and Badler, 1990; Lee, Wei, Zhao and Badler, 1990; Byun, 1991) Another technique is to use experimentally determined human preferences for postures in particular situations, such as seated workers (Hsiao and Keyserling, 1990; Kilpatrick, 1970; Snyder, Chaffin, and Schutz, 1972). The advantage of the algorithms that use human preferences over optimal posture algorithms is that workers often do not assume optimal whole-body postures. Park (1973) compared measured postures to those predicted by optimization routines. While some of the optimization routines were more accurate than others, the measured postures did not match any of the predictions. This would imply that predicting posture is more complicated than simply optimizing the forces on the body. For these reasons behavior-based inverse kinematics algorithms are more accurate than optimal algorithms. A behavior-based inverse kinematics algorithm which is based upon studies performed by Kilpatrick (1970) and Snyder et al. (1972) is described in Chapter 4.

2.3.3 Videographic methods

The decreasing prices of video cameras are making them an essential tool for ergonomists. Since such cameras are widely available, the questions to ask is whether or not three dimensional working postures can be measured directly. Most videographic systems require the use of markers to be placed upon the workers and sophisticated video processors. The major disadvantages associated with such systems for field studies were outlined by Wrigley, Green, and Briggs (1991) and Woltring (1984). These disadvantages are: (i) expense (up to $50,000 per system), (ii) complex set-up and calibration procedures

required, (iii) on-site computer required, (iv) obtrusive in size, (v) specialized front-end hardware required to detect joint markers and (vi) considerable interaction required to produce useful information from raw data. The key reason for the complexity of the equipment is three dimensional coordinates cannot be obtained from a single camera, therefore up to four cameras must be used. While Wrigley, Green and Briggs (1991) describe a viable system for collecting two dimensional data using a videographic system, their system requires orthogonal views of the workplace (i.e. side view or front view) However, because factories generally are densely packed, severe restrictions are placed on the locations of the cameras. This means that orthogonal views are often unavailable. Therefore, although videographic systems can be very effective in collecting data in the laboratory, they are not yet practical for widespread use in real industrial situations.

It should also be noted that videographic methods cannot be used for design unless the workplace is simulated at great expense. This means that videographic methods are used almost exclusively for analysis.

CHAPTER III

THE LIMITATIONS OF CURRENT METHODS OF ENTERING POSTURES

3.1 Introduction

In order to determine the extent of the problems with the current methods of entering postures, representative methods were tested to determine if they were adequate in terms of posture entry time and accuracy. The two main categories of posture entry methods which are currently in use are categorical and joint angle methods, as discussed in Chapter 2.

The best way to test the accuracy of a posture entry method is to have subjects enter postures based upon photographs of a worker whose posture has been accurately measured. This allows the accuracy of the entered postures to be assessed. While many different methods exist for measuring postures (Chaffin and Andersson, 1991), the method chosen for this research uses ultrasound (Hsiao and Keyserling, 1990). In order to be able to simulate working conditions as closely as possible, the worker in the photograph must be wearing normal work clothes with few clues to indicate the locations of the centers of rotation. Videographic methods require reflective markers to be placed on the joints of the worker. The ultrasound method, however, does not require reflective markers on the joints and therefore allows more realistic photographs.

The first posture entry method evaluated was a categorical method (based upon categories developed by the Center for Ergonomics (1990), Keyserling (1986a), and Armstrong (1986)), which requires only a pencil and coding form to be used. If categorical methods are fast and accurate, then the expense of computers is not necessary. A current computerized posture entry method, the joint angle definition menu method, was also tested. If this method is fast and accurate then additional research into more complicated human-computer interfaces is not necessary.

A final experiment tests whether or not a the use of a three dimensional graphic human form model to portray the entered posture is beneficial. The most common method of depicting posture is stick figures, which portray posture poorly. The main disadvantage of using three dimensional graphic human models is the increased amount of computation required.

3.2 Measuring working postures using the ultrasound method

The purpose of this experiment was to measure working postures using the ultrasound method and to photograph the postures. This yields photographs of measured postures. The ultrasound equipment is described in Hsiao and Keyserling (1990). The ultrasound system works by attaching transmitters to the subject's body which emit ultrasound waves. These invisible waves are detected by receivers located around the work area. The time required for the ultrasound wave to travel from a transmitter to a receiver is used to calculate the distance between the transmitter and receiver. This information is used to calculate the positions of the transmitters in three dimensional space.

The work postures assumed by the subject simulated three different kinds of tasks; lifting, push/pull, and hand tool use. Three types of postures were simulated for each task; easy, medium and hard. Easy tasks were strictly in the sagittal plane. Medium tasks were

not in the sagittal plane but involved no lateral bending or axial rotation. Hard tasks were not in the sagittal plane and involved either lateral bending, axial rotation or both.

3.2.1 Subject

The subject used in this experiment was a 27 year old female who weighed 50 kilograms and was 165.6 cm tall. Additional anthropometric data are shown in Table 3.1. All of the link lengths were measured from center of rotation to center of rotation. The link length proportions of the subject did not match those estimated by Drillis and Contini (Chaffin and Andersson, 1991). The subject's legs and arms were shorter than predicted and the torso was longer. The link lengths predicted by the Drillis and Contini constants are also shown in Table 3.1. All measurements were taken with the subject in a neutral posture.

TABLE 3.1 *Comparison of actual versus predicted link lengths*

	Subject data (cm)	Drillis and Contini prediction (cm)
Height	165.6	----
Floor to hip	81.8	87.7
Floor to ankle	7.2	6.5
Floor to shoulder	132.5	135.4
Floor to elbow	104.5	104.3
Hip width	33.5	31.6
Lower arm length	28.5	33.1
Upper arm length	27.5	30.8
Lower leg length	38.8	40.7
Upper leg length	35.8	40.5
Shoulder width	15.2	17.2

3.2.2 Equipment

The following items were used in this experiment:

1. Anthropometer: An anthropometer (sliding calipers, GMP brand) was used to obtain all of the anthropometric measures

2. Goniometer: A goniometer (GMP brand) was used to measure the leg angles

3. Ultrasound measurement system: The ultrasound measurement system (Hsiao and Keyserling, 1990) used 12 transmitters and 8 receivers to measure three dimensional locations. The 12 transmitters were placed on the subject in the following locations; the left lateral-surface mark of the hip, the right lateral-surface mark of the hip, the left palmar crease, the right palmar crease, the medial side of the left elbow, the lateral side of the left elbow, the medial side of the right elbow, the lateral side of the right elbow, the anterior side of the lessor tubercle of the left shoulder, the posterior side of the greater tubercle of the left shoulder, the anterior side of the lessor tubercle of the right shoulder, and the posterior side of the greater tubercle of the right shoulder. The reason there are two transmitters on opposite sides of the center of rotations is so the actual center of rotation can be calculated as an average of the two transmitters. Eight receivers were positioned on poles around the work area (similar to Hsiao and Keyserling, 1990).

4. Camera: A Polariod Impulse™ camera was used to take color photographs of the working postures.

5. Clothes: The subject wore work clothes which were modified so that the transmitters protruded from the clothing. This was done to insure that the photographs of the subject looked as natural as possible and the transmitters were not easily visible in the photographs.

6. Computer: An IBM PC computer was used to collect and store the three dimensional location data.

7. Tote box: A tote box measuring 26.5 x 16.5 x 7.5 centimeters and weighing one kilogram was used to simulate lifting task hand postures.

8. Hand tool A Black and Decker heat gun was used to simulate hand tool handling arm postures.

9. Hand cart: A hand cart was used to simulate push/pull tasks. The cart handle was positioned 78.5 centimeters above the floor. The handle was 40.5 centimeters wide.

3.2.3 Procedure

At the beginning of the experiment, the anthropometric measurements were taken using the anthropometer. Then, the transmitters were fixed on the subject and the work clothes were donned. Finally, the subject was asked to simulate the different work postures. The subject was instructed to "assume a natural posture" while simulating the

task and asked to maintain the posture while the ultrasound data collection was performed. A photograph was taken and the angles of the legs were measured with a goniometer. Because of the small amount of force that the subject had to exert, no difficulty was observed in holding a posture for the duration of time required to collect the data. The order of the tasks is shown in Table 3.2. The subject was given as much rest as desired between the different tasks. Digitized copies of the posture photographs are presented in Figures 3.1 to 3.11. The actual photographs were in color.

TABLE 3.2 *Order of the postures assumed by the subject*

Task	Type of posture
Lift	Easy
Lift	Medium
Lift	Hard
Push/pull	Easy
Push/pull	Medium
Push/pull	Hard
Hand tool	Easy
Hand tool	Medium
Hand tool	Hard



Figure 3.1 *Test posture 1 (easy)*

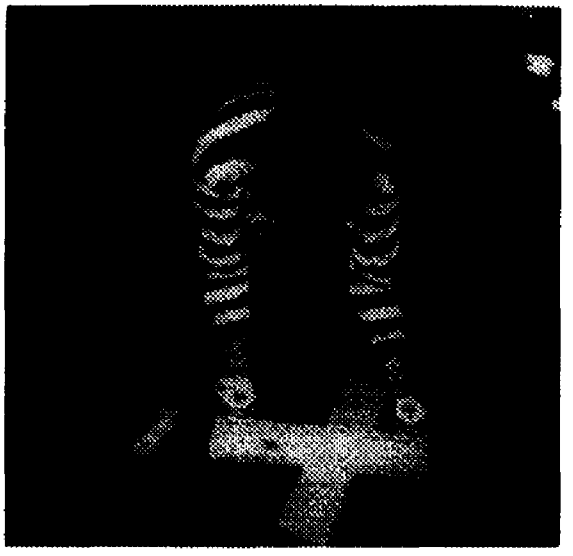


Figure 3.2 *Test posture 2 (hard)*



Figure 3.3 *Posture 1 (easy)*



Figure 3.4 *Posture 4 (easy)*

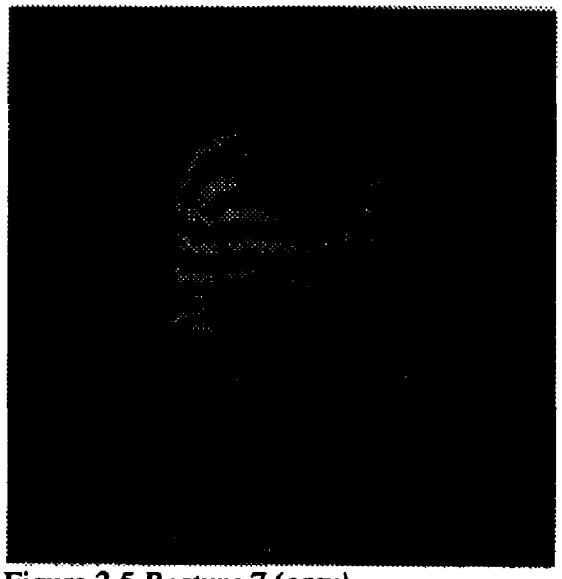


Figure 3.5 *Posture 7 (easy)*

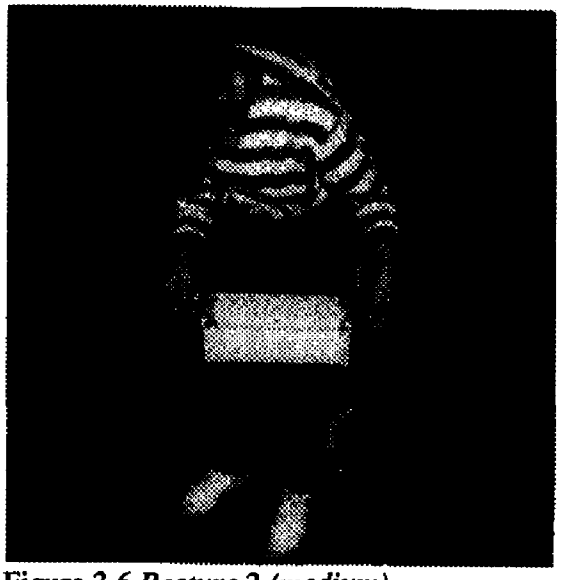


Figure 3.6 *Posture 2 (medium)*



Figure 3.7 *Posture 5 (medium)*



Figure 3.8 *Posture 8 (medium)*

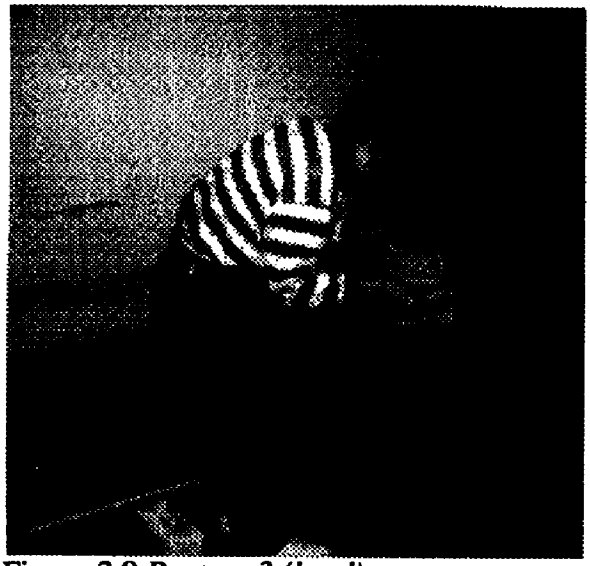


Figure 3.9 *Posture 3 (hard)*

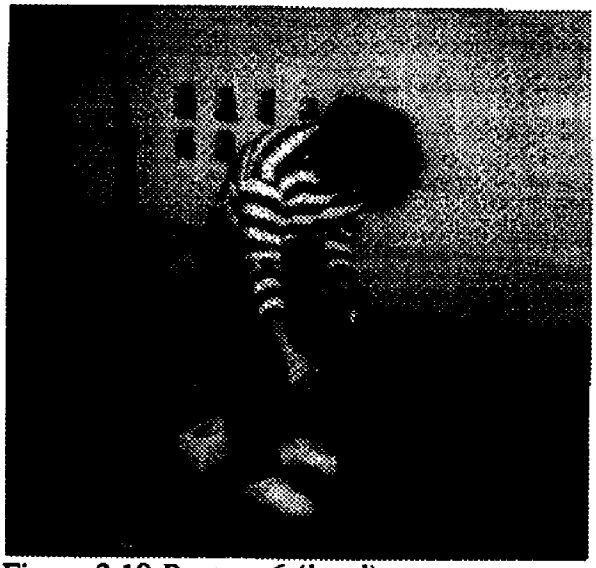


Figure 3.10 *Posture 6 (hard)*

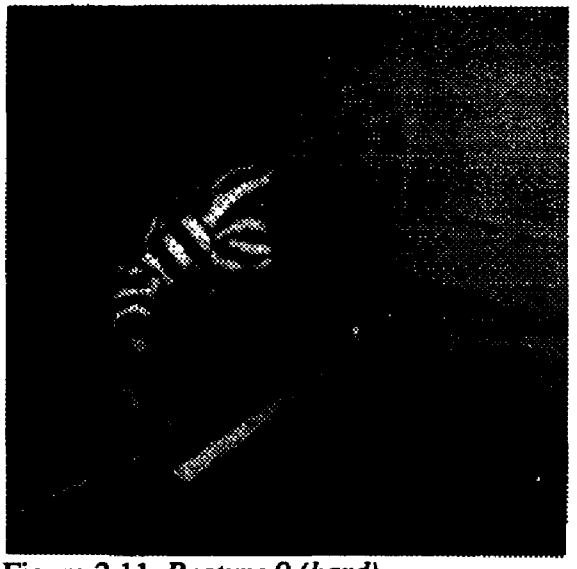


Figure 3.11 *Posture 9 (hard)*

Once the three dimensional posture data had been collected, they were analyzed to determine the position of the joint centers of rotation. While the positions of many of the centers of rotation were clear from the data, other joint centers needed link length data to help determine their position. Certain centers were not easily determined because some transmitters were obstructed by body parts or clothing. The link length data was used to verify that the centers of rotation were accurate to within about one inch. Because centers of rotation change throughout the range of motion (Chaffin and Andersson, 1991), it is not possible to determine their exact location. However, based upon the link length data and the accuracy of one centimeter reported by Hsiao and Keyserling (1990), the accuracy of the ultrasound data can be considered to be sufficient (within 3 degrees per joint) for the purposes of this experiment.

The joint angles were calculated from the joint centers of rotation. The range of values for each type of angle are shown in Table 3.3. The data from the test postures are not included. Notice that the range of values for the legs are relatively small, which means that the leg postures did not vary greatly from posture to posture. However, the other joint

angles vary significantly from posture to posture. This means that a wide range of postures were represented for the arms and trunk.

TABLE 3.3 *Range of values for joint angles of measured postures*

Angles	Mean angle	Standard Deviation
Right forearm vertical	-18	9
Right forearm horizontal	87	25
Right upper arm vertical	-58	20
Right upper arm horizontal	-48	49
Right lower leg vertical	88	3
Right upper leg horizontal	97	4
Left forearm vertical	-14	9
Left forearm horizontal	103	26
Left upper arm vertical	-70	9
Left upper arm horizontal	-75	36
Left lower leg vertical	88	3
Left upper leg horizontal	97	4
Lateral bending	5	12
Trunk flexion	49	7
Axial rotation	1	10

3.3 Evaluation of a categorical posture entry method

This study was performed to obtain base-line data on the time required and errors committed when using a categorical posture description method, and to evaluate trained and novice users.

3.3.1 Subjects

A total of 10 subjects were used in the categorical method experiment. All subjects were unpaid volunteers who had no previous knowledge of the categorical posture entry method used in this experiment. Five of the subjects were ergonomics students (who had taken at least one course in ergonomics), and the other five had no ergonomics training.

Four of the five nonergonomics students have doctorates in engineering and the other has a masters degree in engineering.

3.3.2 Material

Six photographs of working postures which had been measured using the ultrasound equipment were presented to the subjects. Only the medium and hard postures were used. In addition, graphical descriptions of leg (Center for Ergonomics, 1990), trunk (Keyserling, 1986a), and arm postures (Armstrong, 1986) were used to aid subjects in selecting categories, see Figures 3.12, 3.13 and 3.14.

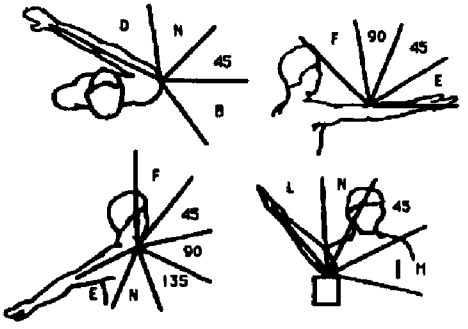


Figure 3.12 *Arm posture categories*

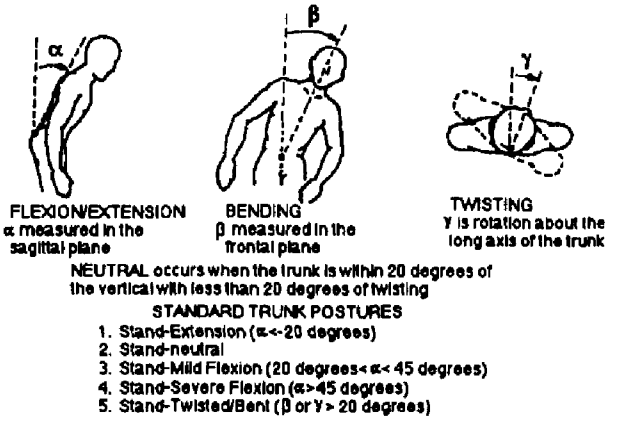


Figure 3.13 *Trunk posture categories*

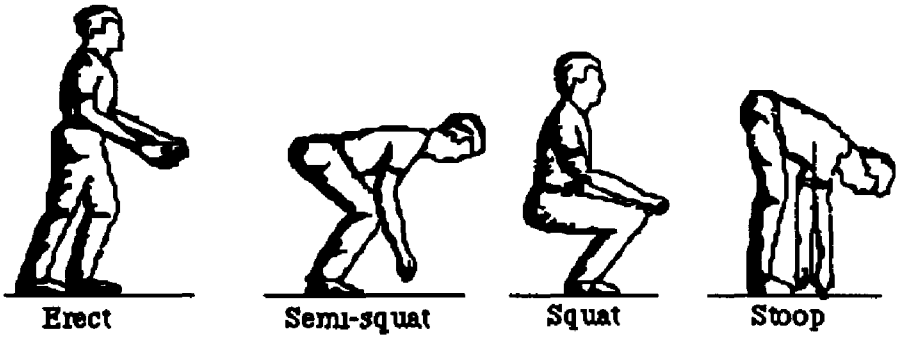


Figure 3.14 *Leg posture categories*

3.3.3 Procedure

The session began by giving the subject the graphical descriptions of the individual body segment postures and explaining how to use them. Once the training was completed, the subject was presented with each of the photographs in random order. The subjects were asked to imagine that they were performing ergonomics analysis and "to select the appropriate categories as accurately as possible without wasting time". The number of correct responses as well as the posture entry time were recorded. Subjects were allowed to rest between trials if desired.

3.3.4 Results

The percentage of correct categories selected for the different parts of the body is shown in Table 3.4. The overall mean percentage of correctly selected categories was 38%. Using an ANOVA analysis, it was determined that the ergonomics students did not have significantly better accuracy than the subjects with no ergonomics training ($F(1,48)=1.406$, $p=0.241$). The trunk postures were significantly easier to enter correctly than the leg and arm postures ($F(2,27)=9.342$, $p=0.001$). The horizontal angles were

significantly harder to enter correctly than the vertical and humeral rotation angles ($F(2,74)=7.390$, $p=0.001$).

TABLE 3.4 *Percentage of correctly selected categories for the different body segments*

Body segment	Mean	Ergonomics students	No ergonomics training
Leg postures	40	30	50
Torso postures	62	57	67
Arm postures	36	41	30
Right upper arm horizontal	18	20	17
Right upper arm vertical	33	43	23
Right humeral rotation	35	37	33
Right elbow vertical	27	33	20
Left upper arm horizontal	18	23	13
Left upper arm vertical	70	80	60
Left humeral rotation	52	53	50
Left elbow vertical	30	37	23
Overall	38 (17)	41 (17)	36 (18)

The mean posture entry time was 239 seconds with a standard deviation of 140 seconds. The ergonomics students had significantly faster posture entry times than the subjects with no ergonomics training ($F(1,48)=20.919$, $p<0.001$). The posture entry times for each group are given in Table 3.5.

TABLE 3.5 *Means and standard deviations for posture entry time using a categorical method(seconds)*

Group	Posture entry time	Standard deviation
Ergonomics students	161	17
No ergonomics training	317	93

The correlation coefficient between accuracy and posture entry time was -0.261. Using the t test technique, ($t(0.975,58)=2.00$, $t^*=4.52$) the conclusion is that the two

variables are not independent. A speed/accuracy tradeoff would have been indicated if the correlation had been positive.

3.3.5 Discussion

The results of this experiment demonstrate that estimating body angles accurately from a photograph is not an easy task. Even the ergonomics students were correct only 41% of the time. This implies that an ergonomics analysis based upon the categories selected by the subjects would frequently be in error. Some of the mistakes made by the subjects, however, can be attributed to postures that were close to the boundaries of two categories. In particular, many of the leg postures and upper arm horizontal postures were difficult to determine, which explains why the subjects had more trouble with these postures. One way to alleviate the boundary problems is to change the definition of postures from discrete categories to continuous angle values. Several computerized systems use this technique including the 3DSSPP™ (Center for Ergonomics, 1990) and EDGE (Beck, 1990a).

One other problem that the subjects encountered was lack of feedback. There was no easy way of detecting mistakes. A feature that computers can provide is a three dimensional depiction of human beings with selected postures. This provides some means of determining spatially if the description of the posture is correct.

The amount of time required to analyze a posture was not extremely long (~4 minutes) for both the ergonomists and nonergonomists. However, if the subjects had been provided with feedback, then they probably would have taken more time to try to be more accurate. This could have made describing postures using this technique to be inefficient. Further research needs to determine how much posture entry time is required when feedback is provided.

The relationship between posture entry time and accuracy revealed that slightly less posture entry time was required when the subjects were able to select the correct category than when an incorrect category was selected. The correlation between these two variables is not great enough to draw any strong conclusions, but one possible explanation is that difficult postures take longer to determine but also result in the most errors. Since there was no speed/accuracy tradeoff, there is no evidence that additional posture entry time would improve accuracy.

The results of this experiment indicate that this categorical method is not an effective means of accurately describing working postures because the percentage of correctly selected categories is low. This may have implications for all pencil and paper methods since no feedback can be provided. Computers can provide graphic feedback which will give analysts a means of determining if they have properly described the posture. Therefore, further research into computerized methods for describing postures is justified.

3.4 Evaluation of the accuracy of a joint angle method

The purpose of this experiment is to determine if analysts can enter a working posture accurately using joint angle posture entry methods with feedback. Feedback was provided in the form of stick figures drawn on the computer screen, see Figure 3.15. In this experiment, three different groups of analysts attempted to enter the same working posture based upon the same photograph and videotape of an actual job. Other researchers have used the variability in postures entered as a measure of the accuracy of posture input methods (Keyserling and Budnick, 1987). If the variability of the postures is large, then at least one of the groups has entered an inaccurate posture. Because the working posture used in this experiment could not be measured, the variability of the entered postures was

used as a rough measure of accuracy. If the variability is large, then at least some of the entered postures were inaccurate.

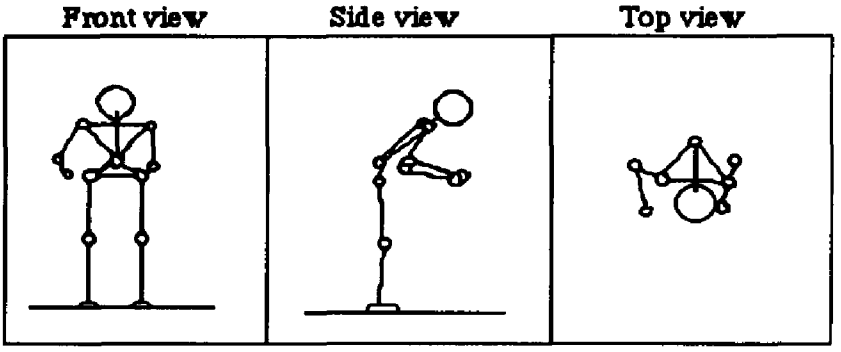


Figure 3.15 *Stick figure representation of a posture*

3.4.1 Subjects

Two groups of five ergonomics students and a professional analyst participated in the experiment, making a total of three groups. The professional analyst performs research in ergonomics as a part of his job and has more than five years experience. The two groups of ergonomics students entered the posture as a part of a class project. The professional analyst entered the posture as a part of an actual ergonomics analysis. The groups of subjects are identified as Groups 1 and 2.

3.4.2 Method

Each of the three groups was given a videotape of an actual job and a photograph of the most extreme posture assumed while performing that job. The photograph is shown in Figure 3.16. The same videotape and photograph were used by all groups. A workstation sketch and the anthropometry of the worker were also provided although the hand locations were not emphasized. The professional analyst used the 3DSSPP™ to

enter the posture, which means that the keyboard joint angle posture entry method was used. The two groups of students were provided with EDGE (Beck, 1989), an ergonomic analysis system which works similarly to the 3DSSPP. The joint angle definition menu method (Figure 2.13) is used in EDGE to enter postures. The posture was relatively complex because the trunk was twisted and the arms were asymmetric.



Figure 3.16 *Photograph of a working posture*

3.4.3 Results and conclusions

The postures entered by each group are shown in Figures 3.17, 3.18 and 3.19. Notice that of the three postures, only the one entered by the analyst has the hands correctly touching the cylindrical object. Furthermore, Groups 1 and 2 did not include any axial rotation and lateral bending which contrasts with the analyst who included significant axial rotation and lateral bending. The complexity of entering a posture probably caused the groups of students to fail to notice that these clues indicate that the entered posture was not correct.



Figure 3.17 *Posture entered by Group 1*

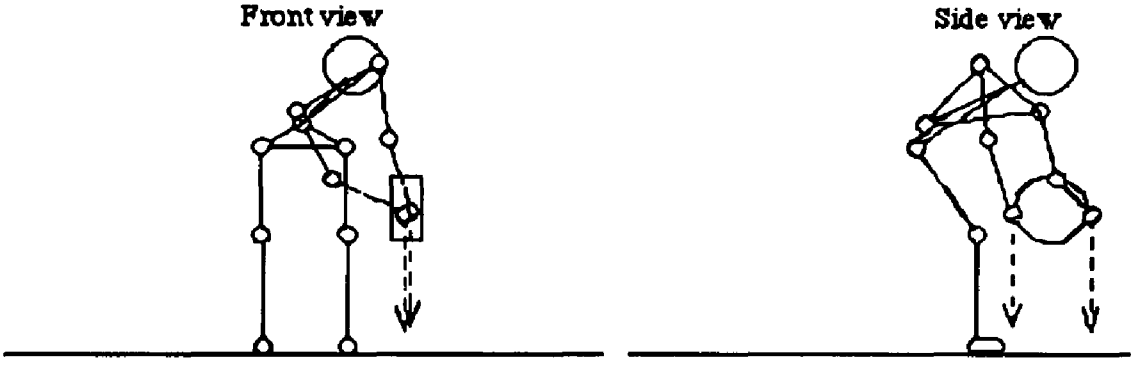


Figure 3.18 *Posture entered by the professional analyst*

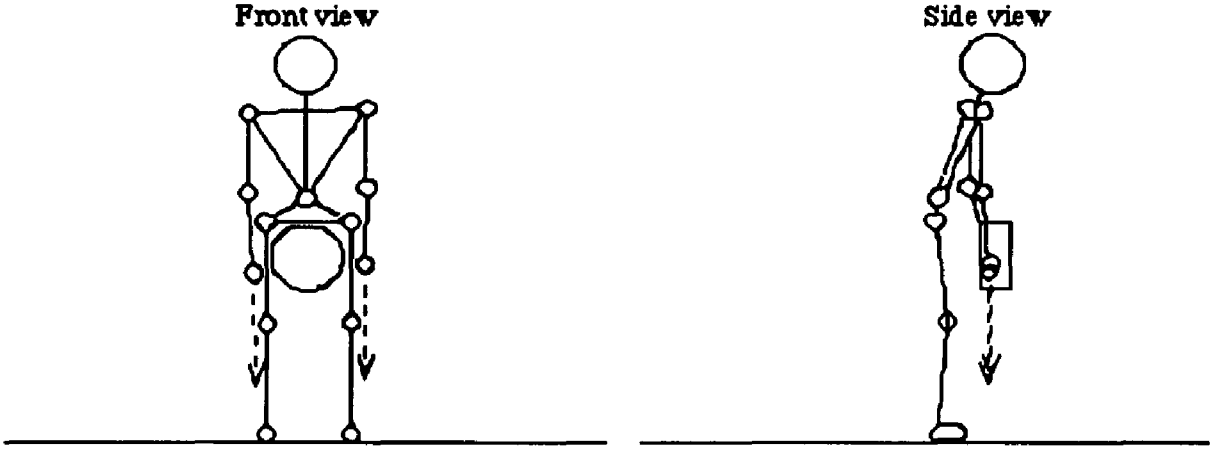


Figure 3.19 *Posture entered by Group 2*

Since there is significant postural variability between groups, this implies that some of the postures are inaccurate. The joint angles entered by the three groups are shown in Table 3.6. However, because the actual posture could not be measured, it is impossible to determine the real accuracy of any of the postures, including the one entered by the professional analyst. These results are consistent with Marshell (1990), who found significant variability in joint angles when a single analyst attempted to enter the same posture multiple times using the keyboard joint angle entry method.

TABLE 3.6 *Postures entered by the three groups of analysts*

	Professional analyst	Group 1	Group 2	Mean	Standard deviation
Right forearm vertical	-30	-70	-80	-60	26
Right forearm horizontal	155	90	90	112	38
Right upper arm vertical	-60	-80	-90	-77	15
Right upper arm horizontal	155	90	90	112	38
Right upper leg vertical	120	100	100	107	12
Right lower leg vertical	90	70	85	82	10
Left forearm vertical	-70	-70	-80	-73	6
Left forearm horizontal	45	90	90	75	26
Left upper arm vertical	-80	-80	-90	-83	6
Left upper arm horizontal	45	90	90	75	26
Left upper leg vertical	120	100	100	107	12
Left lower leg vertical	90	70	85	82	10
Trunk flexion	35	70	80	62	24
Trunk axial rotation	40	0	10	17	21
Trunk lateral bending	-20	0	0	-7	12

These limited results point to the need for further research into the accuracy aspect of posture entry. Even though all three groups of analysts used computers, they did not enter the same posture. This implies that while computers may be useful in providing feedback, the accuracy problems are not necessarily solved.

3.5 Evaluation of the posture entry time of a joint angle method

The objective of this experiment was to determine the amount of time required to enter a posture while using joint angle posture entry methods. If a posture takes a long time to enter, this suggests a weakness in the joint angle posture entry method interface and points to the need for further investigation.

3.5.1 Subjects

The experiment was performed using two subjects who were graduate students in ergonomics. Both of the subjects were novices in the use of EDGE. Both subjects had at least two years experience in the use of ergonomics analysis systems that require posture entry and two years of experience in ergonomics.

3.5.2 Procedure

The task for each subject was to use EDGE (Beck, 1990) to analyze three different jobs. They were provided with user's manuals and a telephone number to call for help, although they received no training. Unknown to the subjects was that through video and audio connections, the experimenter who answered the help-line phone could see and hear the user's session. This insured that all of the help that the experimenter gave, including posture entry, was correct. The posture entry method provided was the joint angle definition menus.

Each subject was given a written description and workstation sketch of three different jobs, but no photographs or videotapes were provided. The goal was to perform an accurate ergonomic analysis of the jobs using EDGE. The analysis of each job required

that several postures be entered. The analysts decided upon the postures to enter based upon their experience. In addition, because no photographs were provided, the analysts did not emphasize accuracy in their postures. They simply attempted to enter a reasonable posture based upon the workstation sketch.

3.5.3 Results and Discussion

The amount of time spent entering postures was quite high, averaging 47% of the total time spent analyzing each job. The average amount of time spent entering postures per job was 36.2 minutes. The job analysis time is shown in Table 3.7. Since each job involved an average of four postures to be entered, then an estimate of the time to enter a posture would be a little over nine minutes. While there is no clear guideline on what is an unacceptable amount of time to enter a posture, nine minutes does seem to be quite long. If a more efficient method of entering postures is available, then the efficiency of performing an ergonomics analysis could be greatly enhanced.

TABLE 3.7 *Time to analyze a task using the joint angle method to enter the posture*

All times are in seconds

Job analysis time	Time spent entering other data	Time to read job description and view workstation sketch	Time spent entering postures
6456	1029	3757	1670
3418	352	1335	1731
2579	238	1303	1038
8181	887	1909	5385
3065	436	644	1985
3774	323	2222	1229

Therefore, further research into the speed aspect of computerized posture entry would seem warranted. Similar to the fact that using a computer was did not necessarily improve accuracy, it also did not guarantee that entering a posture will be fast.

3.6 Evaluation of the impact of a three dimensional graphic human model

In this experiment, the ability of humans to compare photographs of working postures to corresponding computer generated representations was investigated. Two different methods of representing three dimensional postures were used. The first method displays stick figures in three orthogonal views as shown in Figure 3.20. The second method uses a three dimensional, enfleshed graphic human form model in addition to the stick figures, as shown in Figure 3.21. Similar graphic human form models were described by Case, Porter and Bonney (1986), Kroemer (1972), Kuusisto and Mattila (1990), Launis and Lehtela (1990), Lee, Philips, Otani, and Badler (1990), McDaniel (1990), Rothwell (1985), Westerink, Tragter, van der Star, and Rookmaker (1990). The three dimensional graphic human form model used in this research is documented in Beck (1991a). Despite the great interest in three dimensional graphic human form models, no previous research has verified that their use results in improved performance over stick figures. If the stick figures are sufficient to display postures properly, then the computational expense of using three dimensional graphic human form models can be saved.

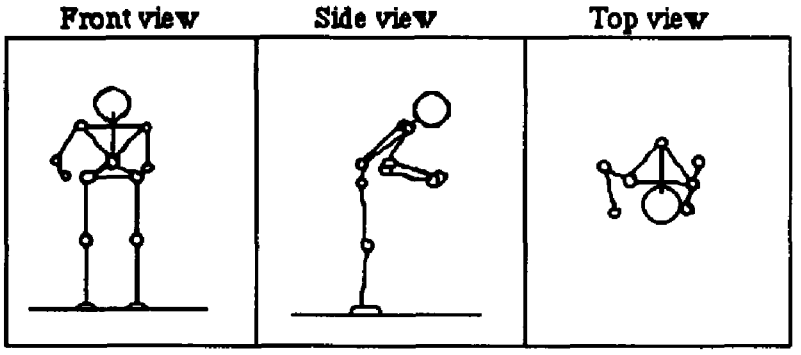


Figure 3.20 *Stick figure representation of a 3D posture*

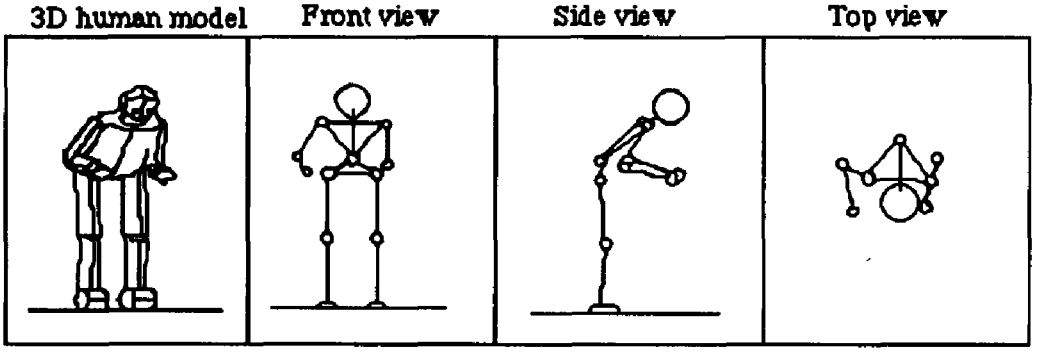


Figure 3.21 *Stick figure representation with 3D graphic human form model*

3.6.1 Subjects

A total of 20 subjects were used in the 3D graphic human form model experiment. All subjects were unpaid volunteers who were not paid for their time and were novices in the analysis of three dimensional postures.

3.6.2 Materials

Six photographs of working postures which had been measured using the ultrasound equipment were used in the 3D graphic human form model experiment. All of the postures included asymmetric hand positions.

Accurate three dimensional representations of each of the postures were generated on a Vaxstation II/GPX computer and printed on a LN03 laser printer. In addition, two deviated representations were generated for each posture. Each deviated representation was significantly different by an average joint angle of at least 20 degrees.

3.6.3 Procedure

Each subject was given the three computer-generated representations of the posture and the photograph. Next, they were asked to select which of the representations was most correct. The subjects were instructed "to be as accurate as possible without wasting time". Half of the subjects were given 3D graphic human form models drawn at the same perspective as the photograph along with the stick figures (Figure 3.21). The other half were provided with stick figures only. Data was collected on the number of correct responses as well as the time taken to answer. Subjects were allowed to rest between trials if desired.

3.6.4 Results

The percentage of correct answers for the 3D graphic human form model group and the stick figures only group were both 64.3% with a standard deviation of 48.5%. Because both groups had the same mean and standard deviation, no significant difference was detectable. No significant subject effect was found ($F(12,70) = 1.348$, $p = 0.213$). Of the 20 subjects that participated in the experiment, only one made no errors.

The mean posture selection time and standard deviation for the group using stick figures only was 26.7 seconds (13.9) while the 3D human model group had a mean posture selection time of 14.6 seconds (10.8). Based upon an ANOVA analysis, it was

determined that there was significant effect on time due to the use of the 3D human form model ($F(1,70) = 33.255$, $p<0.001$). There was also a significant subject effect ($F(12,70) = 5.704$, $p<0.001$).

A comparison was made between the posture entry time for correct answers versus the posture entry time for incorrect answers to identify the possible existence of a speed/accuracy tradeoff. The results are shown in Table 3.8. Notice that the posture entry time for the incorrect answers appears to be slightly higher than the posture entry time for incorrect answers. The coefficient of correlation between correctness and time was 0.085. Using the procedure outlined in Neter et al. (1985) it can be concluded that the two variables are independent ($t(0.975,82)=1.99$, $t^*=0.77$).

TABLE 3.8 *Means and standard deviations for selecting the appropriate representation (seconds)*

	Stick figures only	Stick figures and human form model	Overall
Incorrect responses	29.5 (12.7)	14.9 (12.4)	22.2 (14.4)
Correct responses	25.1 (14.4)	14.5 (10.0)	19.8 (13.4)

3.6.5 Discussion

These results indicate that people have difficulty in estimating whole body postures based upon computer drawn images, since the average number of correct answers was only 64%. How much of the error is due to inherent photographic limitations as opposed to the computerized images remains to be determined. However, if an ergonomics analysis were based upon the postures chosen in this experiment then roughly one third of the time the analysis would be incorrect, based upon the 36% error rate.

Since no speed/accuracy tradeoff was found, it can be suggested that the subjects took sufficient time to make what they considered was an accurate decision. There is no evidence that the accuracy would have improved if the subjects had been encouraged to take extra time.

The use of the 3D graphic human form model was found to reduce the posture entry time but did not improve the accuracy. This result is consistent with mental image rotation and realism research reported by Barfield, Sandford, and Foley (1988). The subjects that had only the stick figures probably used mental image rotation because the stick figures were presented in orthogonal views. The 3D graphic human form model was drawn at the same perspective as the photograph so mental image rotation was not necessary. Barfield et al. (1988) found that mental image rotation increased reaction time but did not have a significant effect on accuracy. They also reported that subjects were able to make correct responses slightly faster than incorrect responses. In addition to the mental image rotation studies, these authors compared the effect of realism on response time and error rates for computer generated objects. They found that response time decreased significantly and error rates decreased only slightly when using more realistic objects.

The results of the 3D human graphic form man model experiment indicate that the use of these models improve posture entry time in posture perception tasks. Therefore, in order to make ergonomics analysts more efficient, 3D graphic human form models are recommended for use in ergonomics analysis systems as opposed to strictly stick figures. However, the 3D graphic human form model does not reduce the number of errors committed by the ergonomics analysts. Additional research is necessary to improve accuracy to meet the Chaffin and Erig (1991) guideline.

3.7 Summary of current posture entry methods experiments

The results of the previous experiments which evaluated the current methods of entering postures demonstrated that these methods are not acceptable in terms of posture entry time and accuracy. The use of computers to enter postures seems to be the preferable approach because of the ability to provide feedback in the form of three dimensional graphic human form models representing the actual posture. Based upon the poor performance achieved with the joint angle posture entry method, however, additional research into computerized posture entry methods is justified.

Since ergonomics analysts demonstrated the difficulty of perceiving postures represented by a picture, then some means of automatically estimating postures would be a possible enhancement. Even if the posture prediction estimate is not accurate, it can at least provide a good first approximate posture to be modified by the analyst using another method of joint manipulation. A behavior based inverse kinematics algorithm for posture prediction is proposed to become the first step in developing a more efficient and accurate posture entry method. It is described in the next chapter (4).

CHAPTER IV

DESCRIPTION OF A BEHAVIOR BASED INVERSE KINEMATICS ALGORITHM

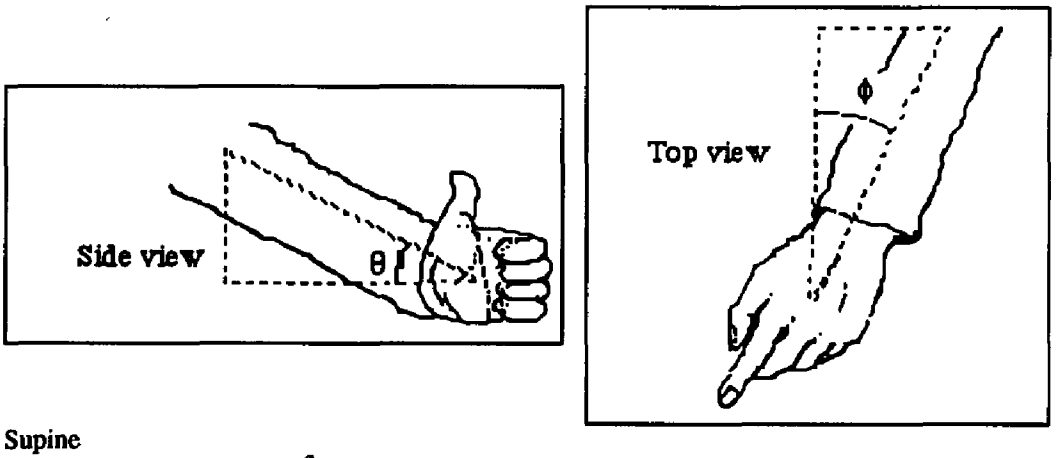
4.1 Overview of the algorithm

This chapter describes a behavior based inverse kinematics algorithm for posture prediction. The development of the algorithm relies on data from Kilpatrick (1970) and Snyder, Chaffin, and Schutz (1972). In both studies, many postures were measured and regression equations developed to predict posture. The purpose of the algorithm is to be able to predict natural working postures based upon minimal input data.

The inputs to the algorithm are 1) the locations of the hands relative to the midpoint of the ankles, 2) the hand orientations (i.e. supine, semi-prone, or prone), and 3) the height and weight of the worker. The midpoint of the ankles is a convenient reference point for designers because it can be estimated visually. The rest of the anthropometry of the worker is estimated based upon the height and weight percentiles of the worker using the Drillis and Contini constants (Chaffin and Andersson, 1991). This is a source of error since the correlation between actual subject proportions and the Drillis and Contini constants is typically poor for at least one link length. The reason that the Drillis and Contini estimates are used as opposed to the actual link lengths is because analysts generally do not have the time to measure link lengths.

The outputs of the algorithm are the positions of each of the body parts. The joint angles are calculated based upon these positions.

Kilpatrick's equations are used to obtain the position of the elbow relative to the hand. The position of the hand is entered relative to the lumbo-sacral joint (L5/S1) of the lower back. The reason that the L5/S1 was used as the reference point was because it was convenient for both seated and standing postures. The posture of the hand can be classified in one of three categories, supine (palm up), prone (palm down), or semiprone. The equations were developed by measuring the position of the elbow relative to the hand of subjects reaching to various points in space. Two angles are used to describe the elbow position, ϕ and θ, (Kilpatrick, 1970). The angle θ indicates the position in the vertical plane and the angle ϕ indicates the position in the horizontal plane shown in Figure 4.1. The distance from the hand to the elbow is calculated by using the Drillis and Contini proportionality constants (Chaffin and Andersson, 1991).



Supine

$\phi = 0.0139X + 0.000106Y^3 - 0.0207Z + 1.35$

$\theta = -0.0153X - 0.000382Y^2 + 0.0324Z + 0.35$

Semiprone

$\phi = 0.000544X^2 + 0.000113Y^3 + 0.915$

$\theta = -0.0118X\ 0.012Y\ -0.000535Y^2 + 0.0348Z + 0.111$

Prone

$\phi = 0.0000142X^3 + 0.0000954Y^3 - 0.0108Z + 0.845$

$\theta = -0.0144X - 0.0478Y^2 + 0.00002034Z^3 - 0.0856$

where X, Y and Z are the coordinates of the hand in space

Figure 4.1 *Descriptions of the angles θ and ϕ (modified from Kilpatrick, 1970)*

Snyder et al. (1972) developed regression equations to predict the positions of major body landmarks (e. g. the top of the shoulder) based upon the elbow positions and anthropometric data as shown in Figure 4.2. The regression equations were developed by measuring the landmarks of subjects who were asked to reach their elbow to various points in space. The regression equations predict the positions of the body landmarks based upon elbow location and whole-body anthropometry. The landmark predictions allow the leg and trunk postures to be estimated. The combination of the sets of equations provides estimated locations for all of the body segments. However, as will be described in detail later, some of the estimated locations may need to be adjusted.

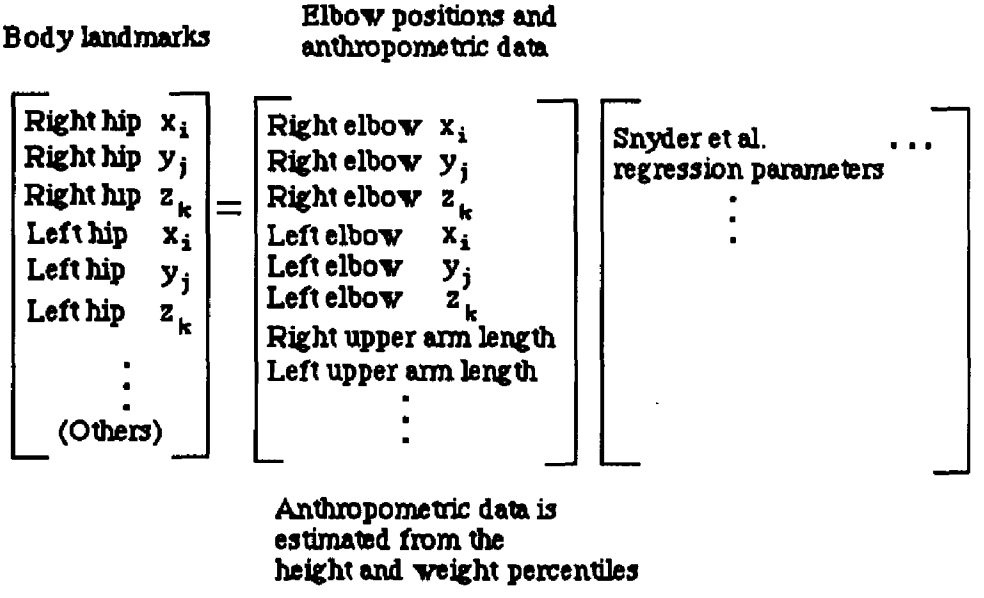


Figure 4.2 *Equations from Snyder, Chaffin and Schutz (1972) used to predict the positions of surface landmarks based upon anthropometry and elbow positions*

4.2 Calculation of the leg posture

Because the human body is composed of three distinct sections, (legs, trunk and arms), the algorithm is divided into three parts accordingly. Each section begins with a diagram outlining the procedure that is used to estimate that portion of the body.

The first step in the algorithm is to determine the posture of the legs. The study by Snyder, Chaffin and Schutz (1972) developed regression equations that predict the position of the L5 surface marker based upon the position of the elbow. The elbow position can be calculated using Kilpatrick's equations (1970), but the position of the L5/S1 must be known. Therefore, each set of equations requires a value that can only be generated by the other set. The only way to circumvent this problem is to first estimate the leg and trunk posture as a starting point and use the equations developed by Anderson, Chaffin and Herrin (1986) to estimate the position of the L5/S1. An algorithm which uses this method is described in Figure 4.3.

Park (1973) reported that workers had a tendency to minimize external work performed when lifting. In lifting tasks, flexing the knees implies greater movement of the upper body. Thus, stoop postures are more common than squat postures, unless the desired hand location cannot be reached except by squatting. In the absence of good behavioral data for the legs, leg postures based upon Park's results were used as indicated in Table 4.1. The regions used by this table are similar to those used by Keyserling (1989) for qualitative analysis of work. The rationale for the leg posture chosen within each region was to keep the worker as erect as possible while still allowing the targeted hand locations to be reached. However, in all cases the estimated postures were balanced. This is a particularly critical issue when reaching to the extended horizontal region. In some cases it was necessary to rotate the hips behind the ankles in order to maintain balance. Moving the hips further behind the center of gravity offsets the load in front.

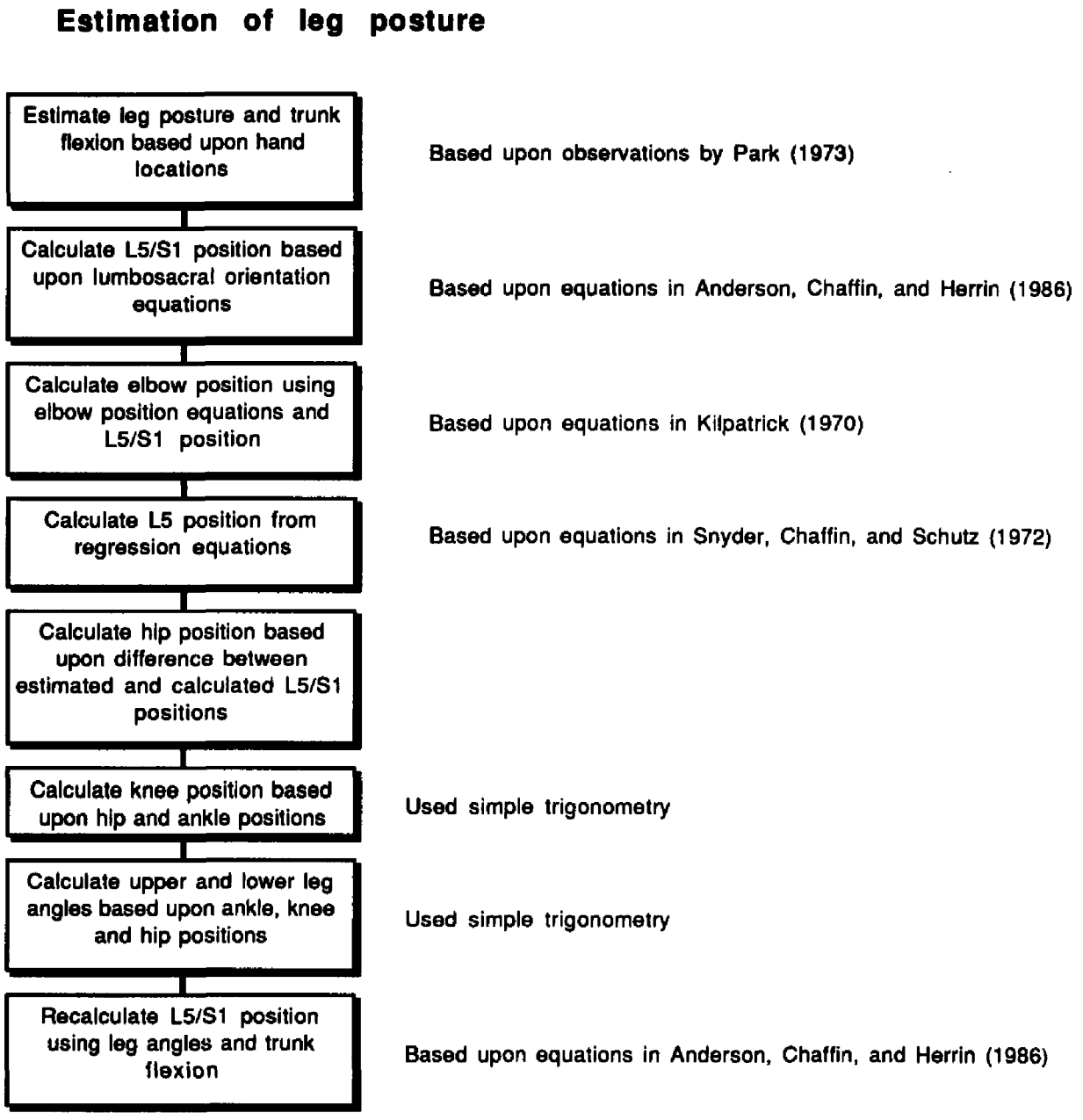


Figure 4.3 *Procedure for estimating leg posture*

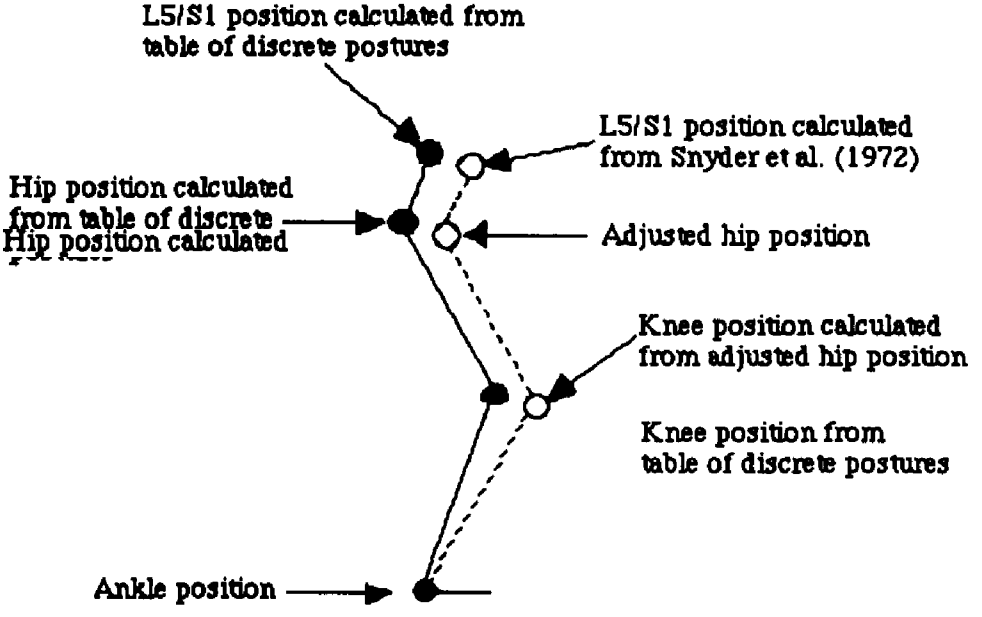
Once the estimated leg postures have been obtained, then it is possible to calculate the position of the L5/S1, a key point in the lower back. The reason that it is important to estimate this position is because the equations of Kilpatrick and Snyder et al. require the

hand locations to be entered relative to the L5/S1. Research performed by Anderson, Chaffin, and Herrin (1986) derived equations for estimating the position of the L5/S1 based upon the leg posture and the trunk flexion angle. At this point, the actual value of the trunk flexion angle is not available, although a good estimate can be obtained based upon the hand locations. Table 4.1 also contains the estimates of the trunk flexion that were assumed for the different regions.

TABLE 4.1 *Discrete postures used in initial estimates of leg and trunk posture*

	Against body	Near body	Mid-range	Extended
Above shoulders				
Between hips and shoulders				
Between hips and knees				
Between knees and ankles				
Below ankles				

The leg posture estimates can be improved, however, by using the Snyder et al. (1972) equations for estimating the position of the L5 based upon the elbow position. Their research also included estimates of the position of the L5/S1 relative to the L5 surface marker, which means that the position of the L5/S1 can be calculated. Since an estimate of the L5/S1 position has already been obtained using the table of discrete postures, then the elbow positions can be calculated from the hand positions using Kilpatrick's equations. The L5/S1 position estimated using this method can then be compared to the L5/S1 position calculated using the table of leg postures. The difference between these two positions is used to adjust the position of the hip. Once the hip position has been established, then the position of the knee can be calculated. These calculations are illustrated in Figure 4.4.



D = (L5/S1 position from table of discrete postures) - (L5/S1 position calculated from Snyder et al.)

Hip position = Hip position - D
Knee position = Knee position - D
Ankle position = Ankle position -D

Figure 4.4 *Leg posture computation*

4.3 Calculation of the trunk posture

Similar to the calculation of the leg posture, the calculation of the trunk posture requires several steps. These steps are outlined in Figure 4.5.

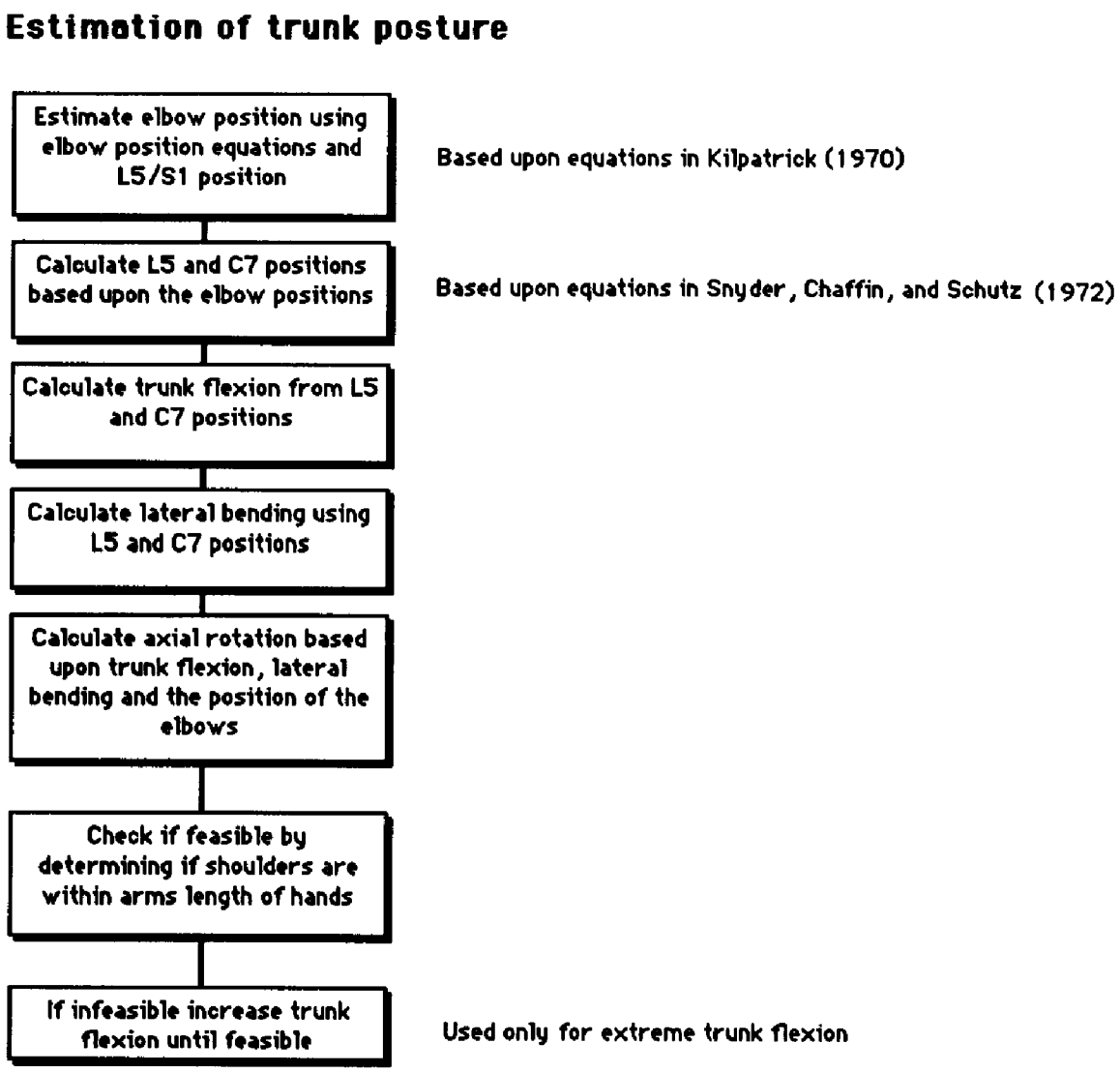


Figure 4.5 *Steps to calculate trunk posture*

The first step in the calculation of the trunk posture is to obtain the position of the elbows based upon the position and posture of the hands using Kilpatrick's algorithm. The next step is to use the regression equations developed by Snyder et al. to get the posture of the back and shoulders. The regression equations use the position of the elbow and anthropometric variables to compute the positions of surface landmarks. This essentially completes the description of the posture of the worker from the standpoint of the behavioral models.

However, while points in space are sufficient for gross estimates of reach and fit, joint angles are needed for more detailed ergonomic analyses such as static strength prediction. While it may seem like a trivial task to convert the points in space to joint angles, there are a few problems to be addressed;

1. The exact position of the joint centers is unknown
2. Joint centers of rotation are not constant, but change throughout the range of motion (Chaffin and Andersson, 1984)
3. The link length proportions of subjects used in the behavioral studies were not consistent
4. Noise exists in the data due to the variability of human preferences

These problems meant that the distances between the estimated joint centers were not constant, but rather varied by as much as 5 centimeters at the shoulders. Therefore, if a human linkage is constructed using Drillis and Contini link proportions and using joint angles calculated from the behavioral data, the resulting hand locations will not be at the target position. This defeats the purpose of the inverse kinematics, which is to position the body in the preferred posture based upon the hand locations.

These difficulties can be overcome if one is willing to accept the behavioral models as being approximately correct. If slight adjustments can be made to the behavioral model data so that the target hand locations are positioned correctly every time, then the algorithm can be considered acceptable. In addition, it is helpful to assume that equations developed

by Anderson, Chaffin and Herrin (1986) for the L5/S1 and by Kilpatrick (1970) for the elbows are acceptably accurate. This is a reasonable assumption based upon validation studies which were performed in each case. However, the Snyder, Chaffin, and Schutz (1972) equations for the shoulders are not as accurate because the shoulder is a very complex joint with numerous degrees of freedom.

Therefore, using the assumption that the Anderson (1986) and Kilpatrick (1970) equations are accurate, the three degrees of freedom for the trunk (flexion, lateral bending, and axial rotation) can be calculated. Trunk flexion and lateral bending can be calculated approximately based upon the positions of the L5 surface marker and the C7 surface marker, which can both be calculated from the Snyder et al. equations. The calculation of trunk flexion and lateral bending is shown in Figures 4.6 and 4.7. The actual positions of the shoulders are not needed to calculate these two angles. However, the axial rotation angle does depend on the positions of the shoulders. Unfortunately, the shoulder behavioral data is quite noisy due to the fact that the scapula can rise (a "shrug") and can also rotate forward. These types of movements are not easily accounted for. In addition, each shoulder must be the length of the upper arm away from the elbow. Since the elbow position is already approximately known, then the axial rotation can be determined by testing each of the available angles in the range of motion and determining which meets this constraint. It is possible that no angle will be acceptable, however. In this case, the axial rotation angle is chosen that makes that shoulders as close as possible to the appropriate distance away from the elbow. Hence, the trunk angles are then fully defined except for a few postures that require extreme flexion. In these cases, the Snyder, Chaffin and Schutz (1972) algorithm tends to underpredict the amount of trunk flexion. However, the trunk flexion can be adjusted forward until the shoulders are within an arm's length of the hands. This trunk flexion adjustment tends to be small. Once the three trunk angles have been

obtained, simple trigonometry and the estimated link lengths can be used to calculate the positions, in three dimensional space, of the shoulders.

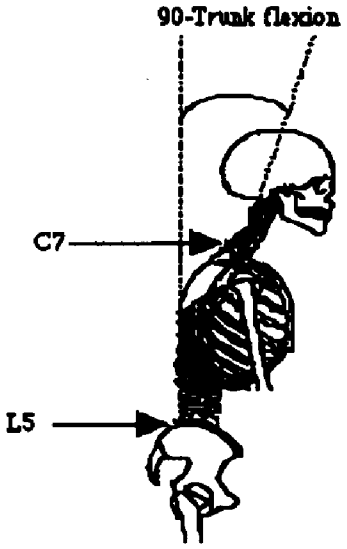


Figure 4.6 *Measuring trunk flexion*

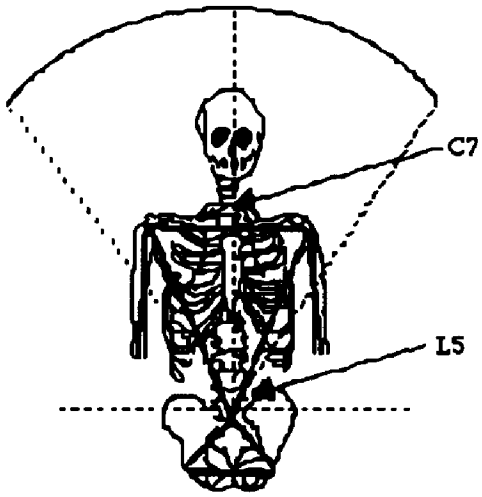


Figure 4.7 *Measuring lateral bending*

4.4 Calculation of the arm posture

Once the trunk angles have been defined, then all that remains is to define the arm angles. At this point, the problem is simple if the elbow is the appropriate distance (as calculated using Drillis and Contini's proportionality constants) from both the shoulder and the hand. Unfortunately, since trunk angles that position the shoulders precisely the correct distance away from the elbows often cannot be found, it tends to be off by at least a small amount. Therefore, corrections must also be made to the elbow position so that the joint angles can be calculated. The steps to accomplish this are shown in Figure 4.8.

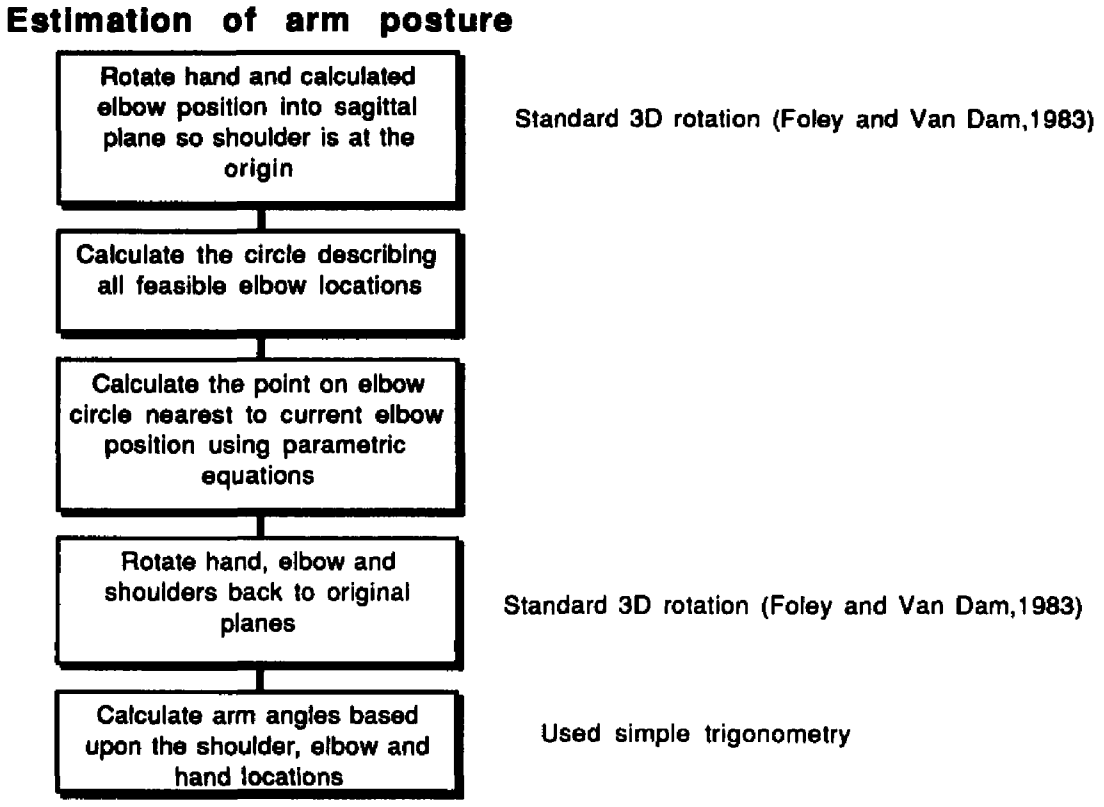


Figure 4.8 *Calculating arm posture*

The position of the elbow can be thought of as lying on the intersection of two spheres, with one sphere centered on the hand and the other centered on the shoulder, see Figure 4.9. The radius of each sphere is defined by the distances to the elbow. The intersection of the two spheres is a circle rotated in space. This circle then defines all feasible locations for the elbow.

This elbow circle is more easily dealt with by rotating the arm such that the circle lies in the horizontal plane. The elbow position that was estimated using Kilpatrick's algorithm can be rotated using three dimensional rotation routines, (Foley and Van Dam, 1983). At this point, what is needed is the point on the elbow circle that is nearest to the estimated elbow position. First of all, the horizontal position of the elbow must lie in the

same plane as the elbow circle. Next, the lateral and vertical positions of the elbow can be calculated using the parametric equations of a line. Hence, once the arm is rotated back into the initial orientation, the elbow position has been defined. Then, all that remains is to calculate the joint angles, which is straightforward using simple trigonometry. At this point, all of the joint angles have been calculated, and the posture is fully defined.

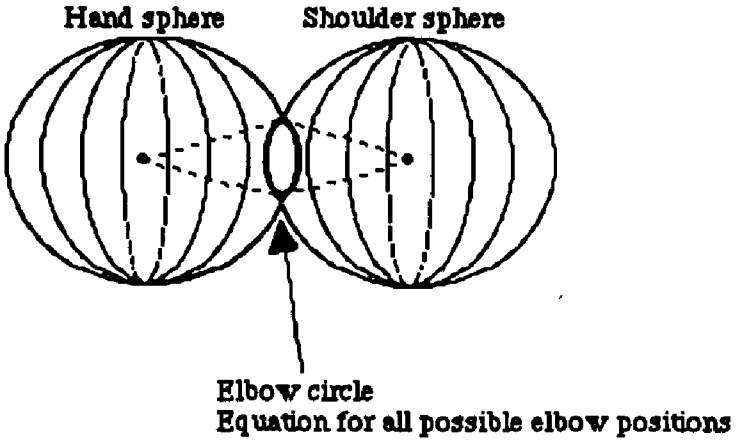


Figure 4.9 *Hand and shoulder spheres with the elbow circle*

4.5 Evaluation of the inverse kinematics algorithm

The preceding behavioral inverse kinematics algorithm was evaluated by testing it against nine postures which had been measured using ultrasound equipment (see Section 3.2). The resulting joint angle differences in terms of degrees are shown in Table 4.2.

TABLE 4.2 *Accuracy of the inverse kinematics algorithm in terms of degrees (difference between predicted and actual angles)*

	Postures									
Angles	1	2	3	4	5	6	7	8	9	Mean
Right forearm vertical	33	14	27	23	29	1	11	16	13	19
Right forearm horizontal	0	1	8	9	5	14	8	5	16	7
Right upper arm vertical	40	2	6	34	19	25	20	4	25	19
Right upper arm horizontal	3	65	70	13	42	0	20	57	85	39
Right lower leg vertical	5	2	8	0	0	0	0	3	2	2
Right upper leg horizontal	16	4	13	3	2	7	3	6	9	7
Left forearm vertical	23	33	15	16	7	6	18	21	23	18
Left forearm horizontal	17	4	11	18	16	17	26	12	2	13
Left upper arm vertical	31	18	26	26	1	68	14	8	7	22
Left upper arm horizontal	3	60	14	6	29	26	40	58	46	31
Left lower leg vertical	5	2	8	0	0	0	0	3	2	2
Left upper leg vertical	16	4	13	3	2	7	3	6	9	7
Lateral bending	4	12	6	4	5	20	5	2	5	7
Trunk flexion	20	20	27	11	13	22	19	31	38	22
Axial rotation	4	19	24	4	17	21	12	4	22	14
Mean	15	17	18	11	12	16	13	16	20	15

4.6 Sources of inaccuracy in the inverse kinematics algorithm

There are a number of reasons for the inaccuracy in the inverse kinematics algorithm. One basic problem is that the link lengths are not entered by the user, but rather are estimated using the Drillis and Contini constants (Chaffin and Andersson, 1984). This means that the link lengths will be generally be off by at least an inch (see section 3.2). If the estimated link lengths are not correct, this means that for the hands to be in the correct location, there must be some differences between the actual and predicted joint angles. Therefore, no inverse kinematics algorithm will be able to predict all of the joint angles exactly unless the actual worker link lengths are measured rather than estimated.

A second source of inaccuracy is that the Snyder et al. (1972) data predicted the positions of surface landmarks. As mentioned earlier, centers of rotation cannot be calculated precisely from surface landmark data because of anthropometric differences. In addition, centers of rotation do not remain constant, but move slightly throughout the range

of motion. This means that there is no way to determine the precise locations of the centers of rotation from the Snyder et al data.

A third source of inaccuracy is the limitation that users can only specify three different orientations for the hands. Since the orientation of the hands is the only means of estimating elbow elevation, whenever the hands are in between two categories some inaccuracy will result. This contributes to the larger errors observed at the arms.

Another possible source of inaccuracy is behavioral differences between people. It is possible for people to move differently simply because of their own preferences. This potentially could explain a major part of the noise in the data.

The inverse kinematics algorithm, by itself, does not have sufficient accuracy such that errors in biomechanical analysis will not occur. This means that additional steps are required in order to enter a posture accurately. The method proposed in this research is to combine the inverse kinematics algorithm with a direct manipulation interface, which is discussed further in Chapter 5.

CHAPTER V

DESCRIPTION AND ANALYSIS OF THE POSTURE ENTRY METHODS USED IN THIS RESEARCH

5.1 The three posture entry methods to be used in this research

Because of the large number of posture entry methods, it was not feasible to evaluate all of them. In order to reduce the total number of methods to be tested, those methods that are unsuitable for use with ergonomics analysis systems were excluded. First of all, no methods were chosen from the categorical class because of the lack of accuracy. In addition, no methods were chosen from the three dimensional digitization class and the videographic class because of the expense of the equipment and the accuracy problems with entering surface coordinates instead of actual joint centers. There are a number of different joint angle entry methods (as described in Chapter 3), but the most commonly used is the keyboard posture entry method. Therefore, the keyboard method of joint angle entry was used to represent the joint angle class of posture entry methods.

Because of the shortcomings of the joint angle methods which were identified in Chapter 3, two new posture entry methods were designed for this research. These two methods, the direct manipulation method and the inverse kinematics method, are described in Section 5.2. An empirical evaluation of these two new methods and the joint angle method is described in Chapters 7 and 8.

In order to make the depiction of entered postures more realistic, all three posture entry methods included a three dimensional graphic human form model which could be viewed from any angle. In addition, three orthogonal view stick figures were provided.

Throughout the rest of the dissertation, the three posture entry methods will be described as "joint angle", "direct manipulation", and "inverse kinematics". These terms will refer to the specific implementations of these methods, and not the classes of posture entry methods.

5.2 New posture entry methods designed for this research

Two new posture entry methods were designed for this research because of the limitations of the current segmental and whole-body posture entry methods. In particular, the joint angle methods require that all users memorize a large number of joint angle definitions. A direct manipulation posture entry method that does not involve joint angles is hypothesized to be a more efficient method. In addition, a hybrid posture entry method that combines direct manipulation of body segments with an inverse kinematics algorithm was also designed. The results of an experiment which compared novice users performance on these new methods to a joint angle method is reported in Chapter 7.

5.2.1 Direct manipulation of body segments

A posture entry method which involves the direct manipulation of body segments as opposed to joint angles was developed for this research. Altering a body posture is accomplished by moving each of the joint centers by selecting the desired position using a pointing device. This contrasts with the joint angle entry method because the user needs no knowledge of joint angle definitions. See Figures 5.1 and 5.2 for an example. The user simply determines where the joints belong and places them there. The computer calculates the joint angles using simple trigonometry.

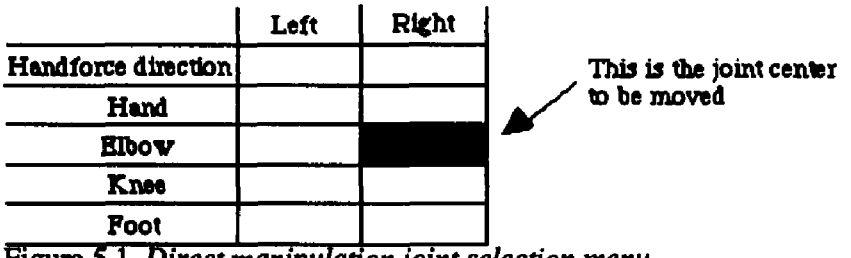


Figure 5.1 *Direct manipulation joint selection menu*

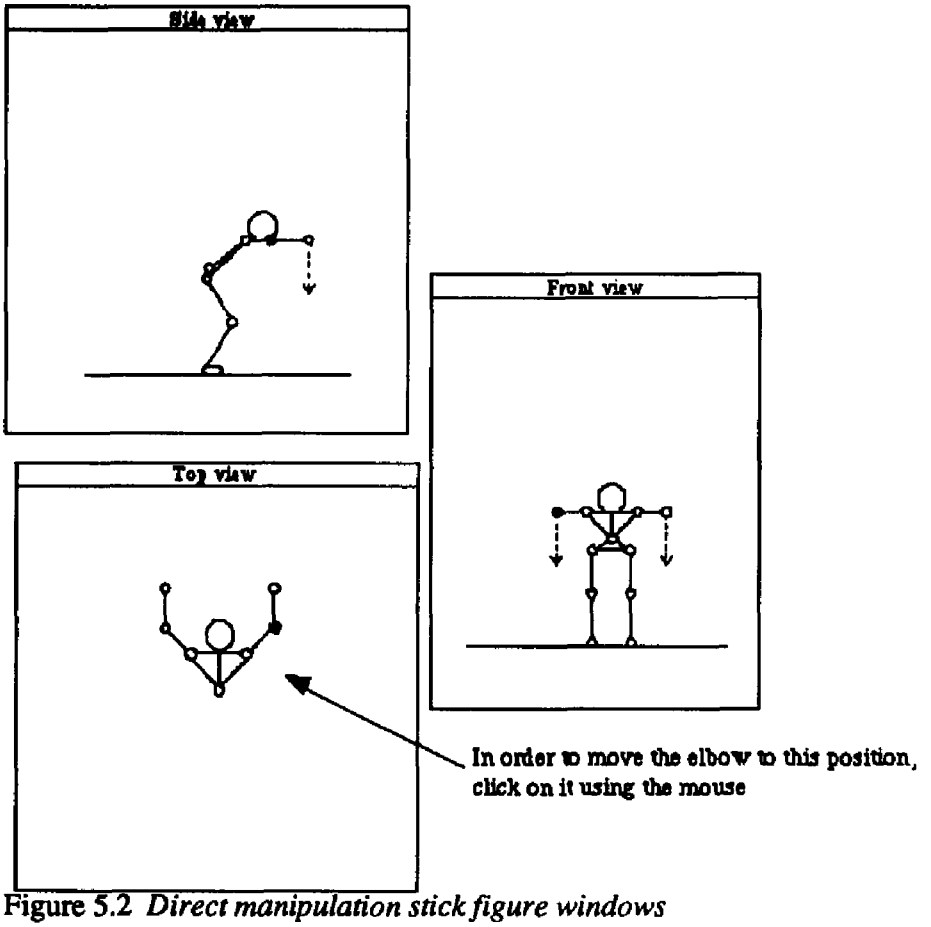


Figure 5.2 *Direct manipulation stick figure windows*

5.2.2 Integration of inverse kinematics with direct manipulation

Inverse kinematics algorithms, while they can make reasonable estimates of posture, may never be able to predict posture adequately. This suggests that inverse kinematics algorithms could be improved if they were combined with a segmental posture

entry method. The posture would initially be predicted by the algorithm and then the users would be able to alter the posture using the segmental method.

The best segmental method to integrate with the inverse kinematics algorithm is the direct manipulation method because of its flexibility. The direct manipulation method uses locations instead of angles which makes it easier to allow different parts of the body to move in an appropriate manner. For example, once the hands have been fixed in space, then the positions of the elbows are required to be exactly one forearm length away. The joint angle interface does not deal with this restriction well, since such manipulations require altering both vertical and horizontal angles simultaneously.

In the inverse kinematics interface, postures are manipulated in a manner similar to direct manipulation in the sense that clicking on the orthogonal view windows selects the new location of a joint. However, in the inverse kinematics interface, the hands are kept in the same location until moved by the user. If any of the other parts of the body are manipulated the hands will still remain in the same location. This means that the user does not have to adjust the locations of the hands, which implies that a little less work needs to be done to enter a posture. A more complete analysis of the differences between the three posture entry methods is in Section 5.3.

Since the hands must always remain in the same location, then whenever one joint position is altered, several other joints may also need to be altered by the inverse kinematics algorithm to keep the hands in the correct location. This can become a problem, if a user moves joint A to the desired location, then moves joint B and the inverse kinematics algorithm modifies the location of joint A. In order to resolve this problem, the inverse kinematics algorithm only estimates joints in between the joint moved and the hands. For example, if the legs are manipulated, the trunk and the arms will be estimated by the inverse kinematics algorithm. Table 5.1 shows the sections of the body predicted by the inverse kinematics algorithm depending upon the body segments manipulated. Therefore, the

logical procedure for users to follow is to first place the hands in the correct location, then manipulate the legs, trunk and finally the arms.

TABLE 5.1 *Sections of the body predicted by the inverse kinematics algorithm*

Manipulated by user	*Predicted by inverse kinematics algorithm*	*Not altered*
Hands	Legs, trunk, and elbows	-
Legs	Trunk, Elbows and Hands	-
Trunk	Arms	Legs
Elbows	Hands	Trunk & Legs

5.3 NGOMSL analysis of the three posture entry methods

5.3.1 Introduction to NGOMSL

The three posture entry methods required interfaces that were well designed in terms of posture entry time. The reason that this is necessary is because the posture entry methods themselves need to be compared as opposed to specific implementations of those methods. If the interfaces are not appropriately designed, then this is a confounding factor. For example, if the interface for one posture entry method required users to type in five characters to perform an action and the interface for another posture entry method required only three characters for the same action, then one of the interfaces needs to be changed unless there is some good reason for them to be different. The interfaces should only differ in ways that are inherent to the posture entry methods themselves.

To insure that all three interfaces were well designed, an analytical method from software psychology was used. This method, known as GOMS, was originally developed by Card, Moran, and Newell (1983) and then was extended by Kieras (1988). GOMS (Goals, Operators, Methods and Selection rules) helps a designer to determine the tasks or goals that the user might wish to accomplish and the steps that are taken to

accomplish them. Each goal is accomplished using methods, which are themselves composed of operators. Selection rules are a means of deciding between different methods. In NGOMSL (Kieras, 1988), the Natural GOMS Language, GOMS was extended to include a basis for estimates of execution and learning time. The NGOMSL analysis of the joint angle method, the direct manipulation method and the inverse kinematics method is included as Appendix E.

The basic operators of the NGOMSL model are shown in Table 5.2. Each step is composed of a number of these operators. The time required for each of the operators is an estimate based upon previous research. The S, M, K, P, and H operators are from Kieras (1988). R is an operator that is used to describe the cognitive activity of converting a position in three dimensional space into a posture manipulation, see Figure 5.3. As such, the time required for R is unknown and can vary between the three different posture entry methods. The estimated value of two seconds for R was based upon mental rotation studies performed by Shepard and Cooper (1982). The other operators should not differ between methods.

TABLE 5.2 *Table of NGOMSL model operators*

	Description	Time required
S	Cognitive cycle	0.1 seconds
M	Mental operator	1.35 seconds
K	Keystroke	0.28 seconds
P	Point using the mouse	1.1 seconds
H	Home hands from mouse to keyboard	0.4 seconds
R	Translate position into posture manipulation	2.0 seconds

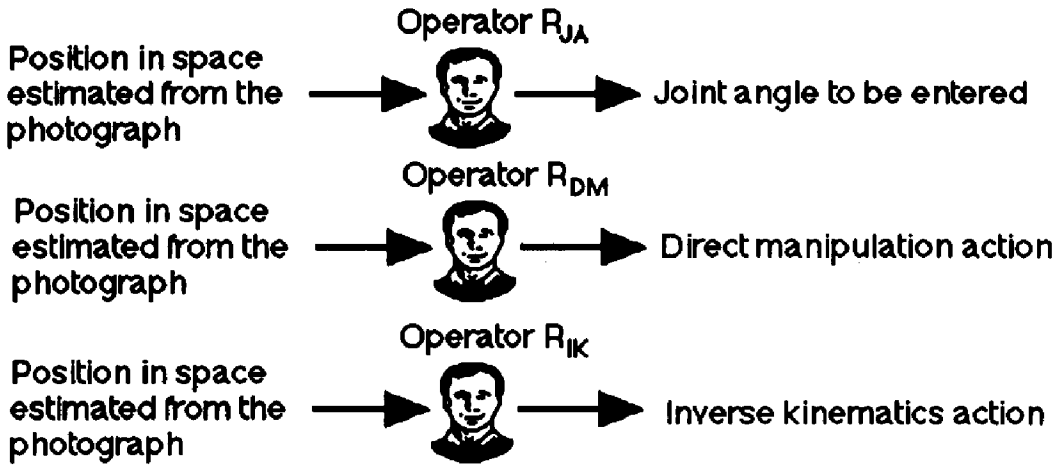


Figure 5.3 *Description of the cognitive operator R*

While NGOMSL analysis is a method for determining performance differences between methods, it was not used for that purpose in this research. The purpose of the NGOMSL analysis was to insure that each posture entry method had been well designed and were as consistent as possible. Therefore, the NGOMSL performance estimates were primarily of interest for each manipulation. No attempt was made to predict the number of manipulations for each method.

5.3.2 Differences between the three posture entry methods

The three posture entry methods differ in the way that the body segments are manipulated. The joint angle method involves simply typing in the appropriate joint angles. The posture entry time is limited only by the number of angles and the typing speed of the user. The direct manipulation and inverse kinematics methods allow the user to point using the mouse to a desired location for a joint. This is reflected in the low number of keystrokes and high number of mouse clicks required. The primary difference between the inverse kinematics method and the direct manipulation method is that the inverse kinematics algorithm automatically places the hands in the proper location. Hence, the

inverse kinematics method has a procedure to type in the hand locations but does not require any manipulations for the hands. This means that the inverse kinematics method requires a minimum of ten posture manipulations in contrast to the direct manipulation and joint angle methods which require a minimum of 15 posture manipulations. The reason that the inverse kinematics method is only slightly faster than the other methods is because of the time required to type in the hand locations.

Within each manipulation, however, the amount of estimated time is quite similar, with the inverse kinematics and direct manipulation methods estimated at 7.11 seconds and the joint angle method at 6.17 seconds as shown in Tables 5.3 through 5.5. Since R is the action that converts a position in space into a posture manipulation, the cognitive activity is by nature different for each of the methods.

Table 5.3 NGOMSL analysis of a direct manipulation posture manipulation

s	M	K	P	H	R	Method to enter segment position by direct manipulation
1		1	1			Select desired segment in joint menu
1	1					Decide upon desired location of segment in 3D space
1						Retain position of segment in 3D space
1	0	1	1		1	Select position
1						Recall position of segment in 3D space
4	0					Accomplish the goal of verifying that the segment is in the correct position
1						Report goal accomplished
10	1	2	2	0	1	Total time in seconds 7.11

Table 5.4 NGOMSL analysis of an inverse kinematics posture manipulation

s	M	K	P	H	R	Method to enter segment position by inverse kinematics
1		1	1			Select desired segment in joint menu
1	1					Decide upon desired location of segment in 3D space
1						Retain position of segment in 3D space
1	0	1	1		1	Select position
1						Recall position of segment in 3D space
4						Accomplish the goal of verifying that the segment is in the correct position
1						Report goal accomplished
10	1	2	2	0	1	Total time in seconds 7.11

Table 5.5 NGOMSL analysis of a joint angle posture manipulation

s	M	K	P	H	R	Method to accomplish the goal of entering a joint angle by keyboard entry
1	1					Decide upon position of segment in 3D space
1						Retain desired segment location
1						Retain the type (horizontal or vertical) angle to estimate
4	0	0	0	0	1	Accomplish the goal of estimating angle
4		4				Accomplish the goal of typing in an angle
1						Recall position of segment in 3D space
4						Accomplish the goal of verifying that the segment is in the correct position
1						Report goal accomplished
17	1	4	0	0	1	Total time in seconds 6.17

The value of R for each method can be estimated from experimental data. If the NGOMSL estimate of the time required for the operators other than R can be assumed to be correct, then the measured time per manipulation can be compared to the predicted time per manipulation minus the value of R. The difference is the value of R. The values of R for each of the three methods are useful for comparison purposes since it illustrates a difference between methods. The values of R for each method are reported in Chapters 7 and 8.

Another factor that can cause significant differences between methods is the number of manipulations. When using NGOMSL, expert behavior is assumed. Therefore, the number of manipulations predicted for each method is a minimum. If one method requires substantially more manipulations than the others, then this may cause it to require more posture entry time. Additional manipulations will be required if users are unable to manipulate a body segment into the proper location on the first try. This could be caused by perceptual limitations (which apply equally to all three methods) or by difficulties with the posture entry method itself. Hence, if one posture entry method requires significantly more manipulations than another, this is an indication that the users find that method harder to use.

To summarize the results of the NGOMSL analysis, the values of R and the number of manipulations will significantly affect posture entry time. The number of physical actions will vary depending upon the method because the inverse kinematics method requires typing in the hand locations and the other methods require users to manipulate the hands into the appropriate locations. If the number of manipulations is small, then the three methods will be approximately the same. However, very large numbers of manipulations will favor the inverse kinematics method in terms of time by about 25% because no hand manipulations are required.

5.4 User interfaces for each of the posture entry methods

The user interfaces for each method are displayed in Figures 5.4 - 5.6. Notice that, consistent with the NGOMSL analysis, all parts of the interface which are not specific to the posture entry method have been standardized.

In order to allow the users to be able to view the Graphic Human Form Model from any angle, a view control interface was included. This allowed users to select the horizontal and vertical orientation.

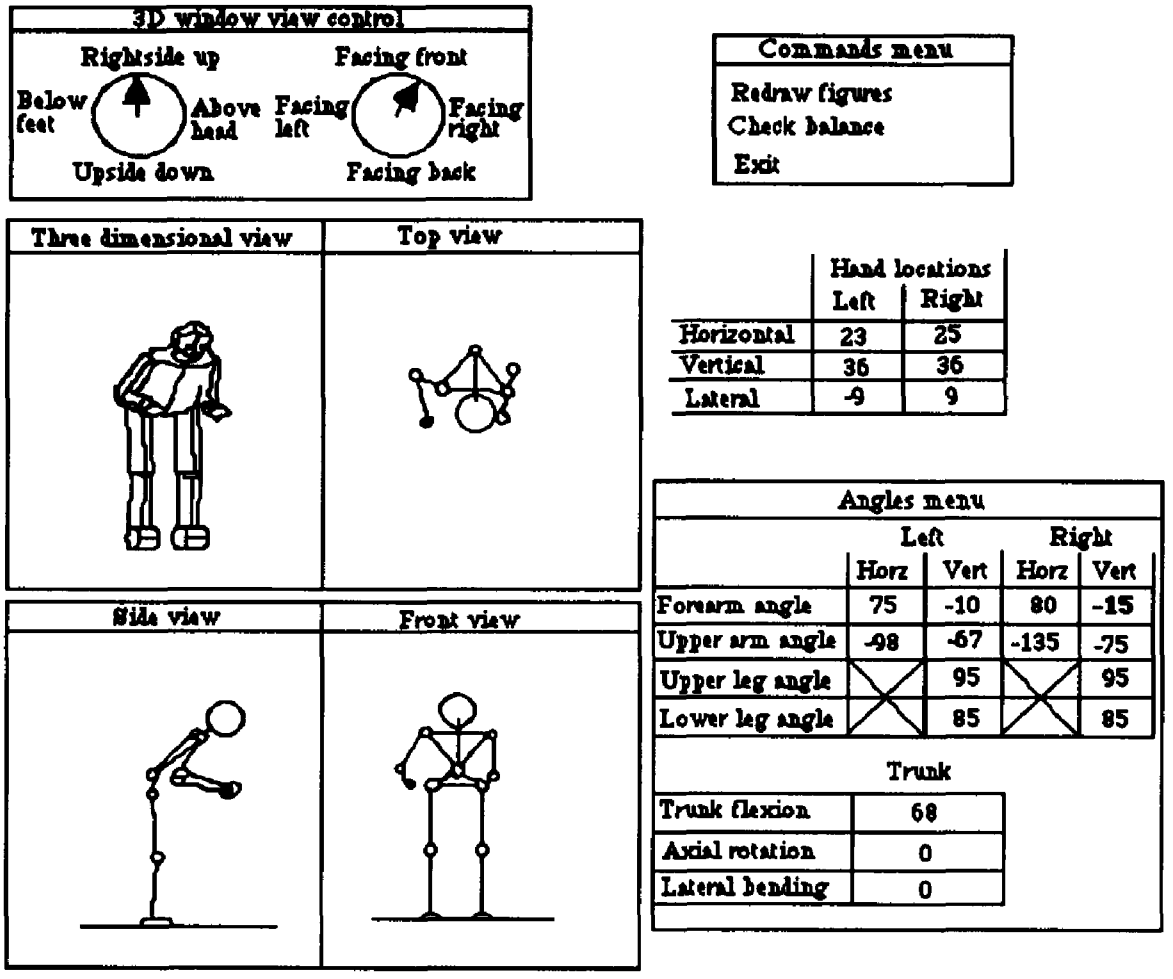


Figure 5.4 *Joint angle interface*

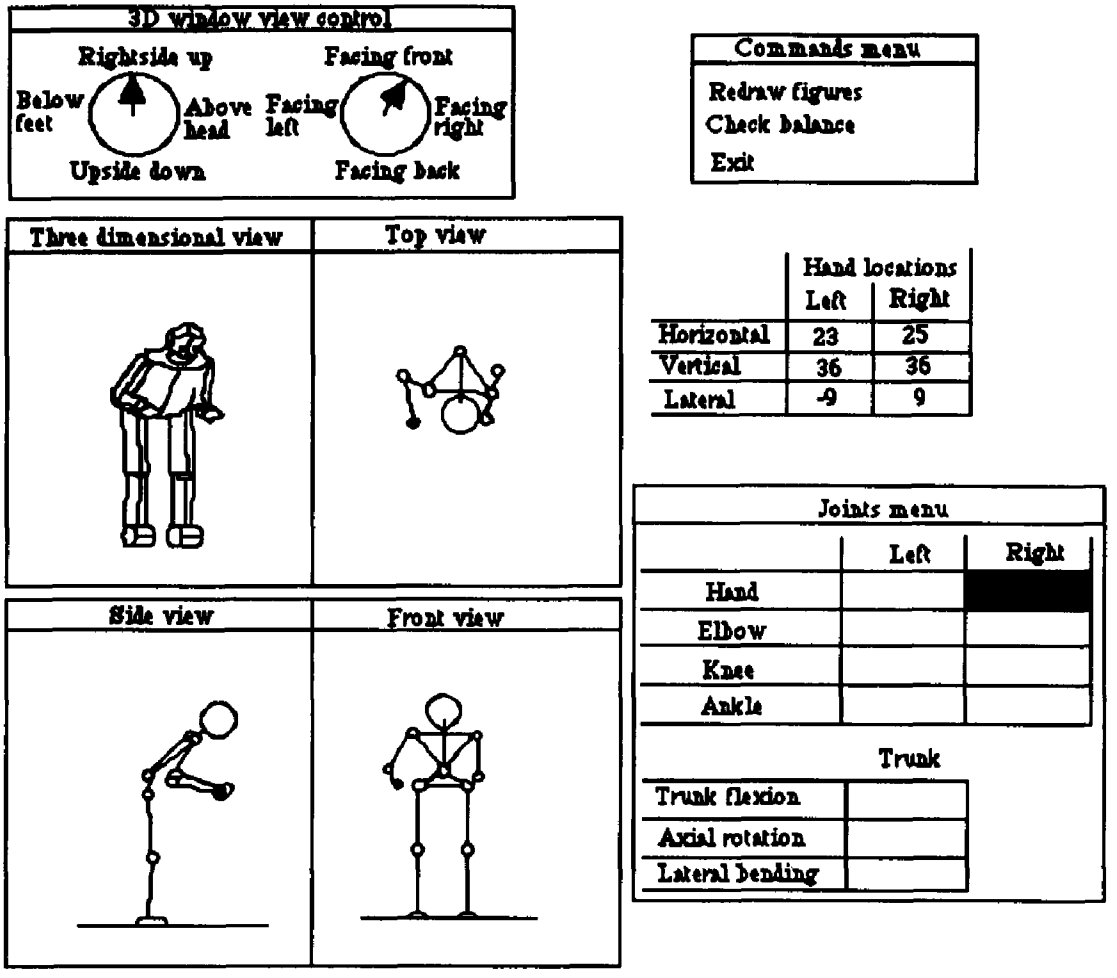


Figure 5.5 *Direct manipulation interface*

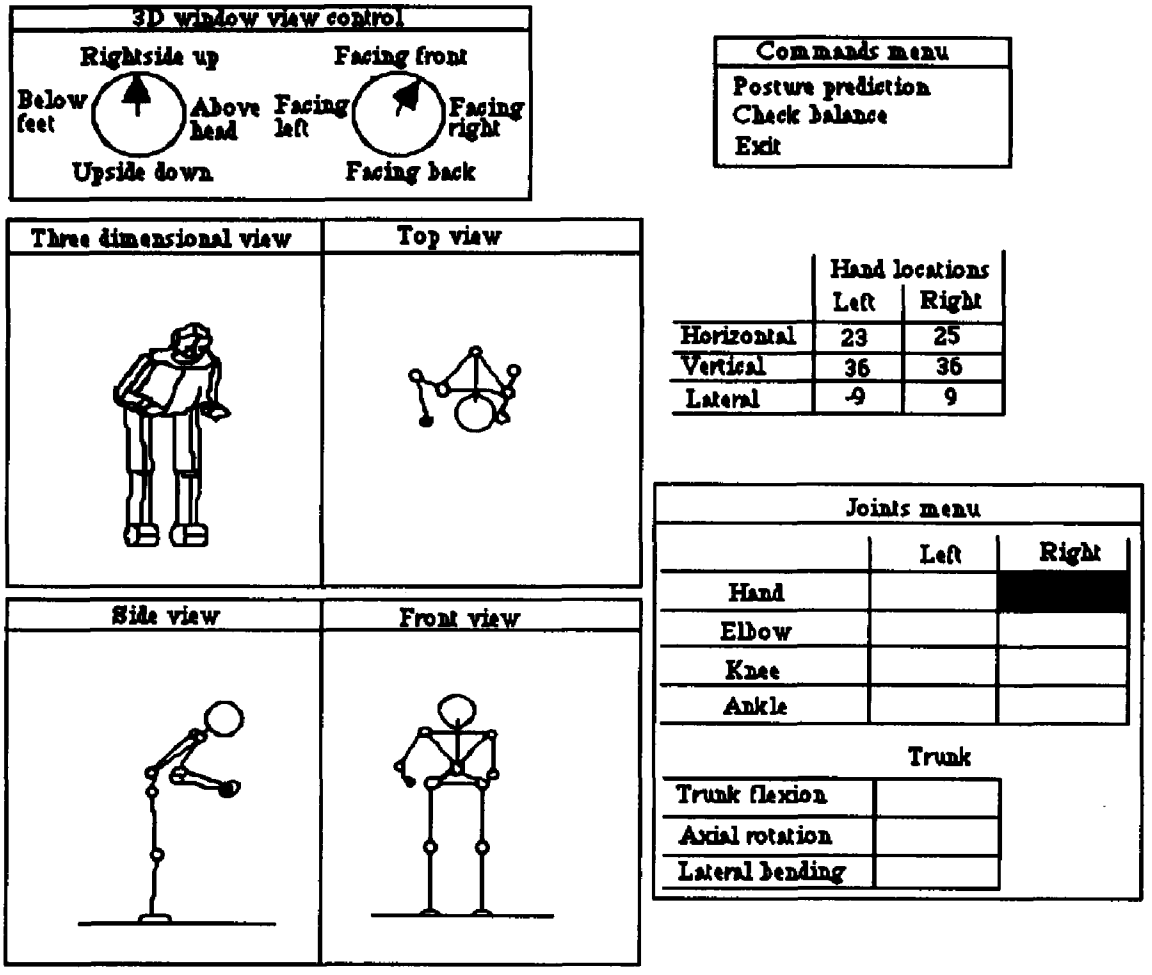


Figure 5.6 *Inverse kinematics interface*

CHAPTER VI

RESEARCH HYPOTHESES AND PILOT EXPERIMENT

6.1 Research hypotheses

In order to be able to test whether the inverse kinematics method is superior to the direct manipulation method and joint angle method for novice users, a number of testable hypotheses were developed. These hypotheses propose that statistically significant differences exist between the three entry methods. The NGOMSL analysis can then be used to help explain why these differences between the methods should exist. The testable hypotheses are shown in Table 6.1.

6.2 Experimental design

Because the NGOMSL analysis is not sufficient to quantitatively determine the magnitude of differences in the posture entry methods, empirical data were collected. For this an experimental design was needed to be able to test the hypotheses of this research (Section 6.1). Considerations of sample size, transfer effects, and the length of the experimental sessions were necessary. The selected experimental design is shown in Figure 6.1. Subjects are nested within posture entry methods. While this nesting increases the number of subjects, it eliminates transfer effects and keeps the length of the experimental sessions to a minimum. For this research, the experimental sessions were

approximately 2-4 hours long. Each subject used a single posture entry method on a total of nine postures. The nine postures were the same for all methods, regardless of posture entry method used.

TABLE 6.1 *Testable hypotheses for posture entry methods experiment*

Posture entry time Hypothesis 1-3
Ho: There is no significant difference in posture entry time for each of the three methods to enter the postures. Ha: There is a significant difference in posture entry time for each of the three methods to enter the postures.
Accuracy Hypothesis 4-6
Ho: There is no significant difference in accuracy for each of the three methods. Ha: There is a significant difference in accuracy for each of the three methods .
Number of manipulations Hypothesis 7-9
Ho: There is no significant difference in number of manipulations required for each of the three methods. Ha: There is a significant difference in number of manipulations required for each of the three methods.
Time per manipulation Hypothesis 10-12
Ho: There is no significant difference in the time per manipulation between each of the three methods Ha: There is a significant difference in the time per manipulation between each of the three methods

The easy, medium, and hard postures refer to the postures that were measured with the ultrasound equipment and then photographed (Section 3.2). The easy postures were entered first, followed by the medium postures and then the hard postures. The reason for this ordering was to follow the subject's learning curve. The postures were randomized within each category of posture difficulty. Within each type of posture difficulty group, three different tasks were represented, 1) lifting, 2) cart pushing and 3) hand tool use.

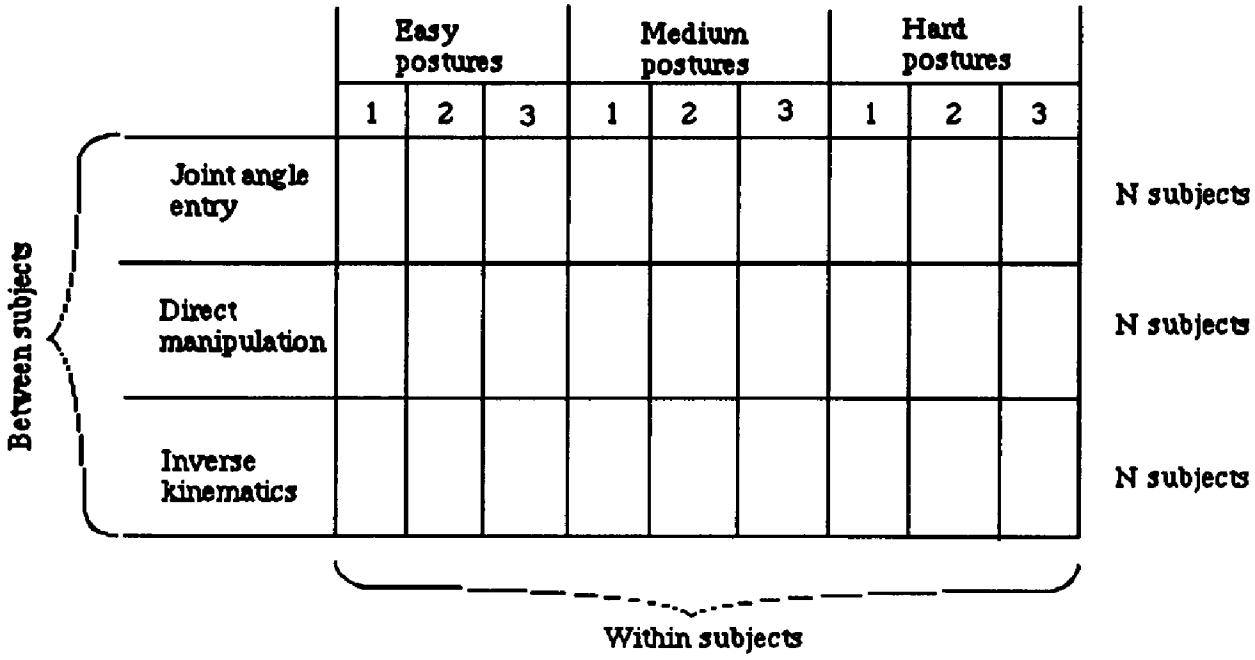


Figure 6.1 *Experimental design*

The dependent variables were final postural accuracy relative to the measured ultrasound postures and posture entry time. The independent variables were the subject effect, the posture entry method effect, the difficulty rating of posture effect and the interaction between posture entry method and posture difficulty.

6.3 Materials and equipment

A list of materials and equipment used in the experiment is shown in Table 6.2. The photographs of working postures were described in Section 3.2. The posture entry methods software with embedded data collection routines was written for this research. The training documentation was developed iteratively using four pilot subjects for direct manipulation and inverse kinematics methods and three pilot subjects for the joint angle

method. The final version of the documentation is available as a technical report (Beck, 1991b). The background and post experiment surveys are in Appendix B. An example data file is included as Appendix C.

TABLE 6.2 *List of materials and equipment for posture entry methods experiment*

Photographs of working postures
Posture entry methods software
Training documentation
Vaxstation 3100 model 38 computer
Background survey
Post experiment survey

6.4 Methods

After filling out the background survey, each subject was randomly assigned one of the three posture entry methods and trained to use that method. This training session began with the documentation being read aloud to the subject. A demonstration of the use of the software was also included. The subjects were encouraged to ask questions of the experimenter during the course of the training. The training provided information on the specific posture entry method as well as a general background of the problem. Altering the view angles of the three dimensional graphic human model such that they matched the view angles of the photograph was emphasized. The last two sections in the documentation emphasize the importance of entering accurate postures without wasting time. The research reported by Chaffin and Erig (1991) that an error of 10 degrees at one joint could alter an ergonomics analysis was also emphasized.

The subjects were then asked to enter two practice postures after viewing photographs. The correct locations of the hands were provided. While entering the practice postures, the experimenter was available to answer questions. The subject was not allowed to continue until a baseline accuracy was achieved. The baseline accuracy levels for

the three posture entry methods are shown in Table 6.3. The baseline accuracy levels insure that each subject has adequate knowledge of how to enter a posture. The accuracy levels were chosen such that each group received approximately the same amount of practice. Each subject was instructed that the practice postures were for learning purposes only and that entering the practice postures according to criterion did not necessarily mean that they were sufficiently accurate.

TABLE 6.3 *List of baseline accuracy levels*

Method	Accuracy
Keyboard method	17 degrees
Direct manipulation method	16 degrees
Inverse kinematics method	13 degrees

After completion of the training session and practice session, the subjects were asked to enter a series of nine postures. Similar to the practice postures, the subjects were supplied with the correct locations of the hands. They were instructed to not ask questions of the experimenter. The training documentation was available for the subjects to consult if desired.

The decision that a posture was entered accurately enough was made by the subjects. Unlike the practice postures, no feedback on the accuracy of the posture was provided in order to simulate industrial conditions. This procedure continued until the subjects had entered all nine of the postures, although the subjects were allowed to take breaks between trials if desired. Once the nine postures had been entered the subjects were asked to fill out the post experiment survey (shown in Appendix B).

6.5 Pilot experiment

6.5.1 Introduction

The purposes of the pilot experiment were the following;

1. To validate the experimental design
2. To validate the posture entry methods software
3. To determine changes necessary in the training materials

The training materials were altered numerous times during the course of the pilot experiment. This means that the results of the pilot experiment cannot be used to determine the research hypotheses or the validity of the thesis statement. However, the pilot experiment does demonstrate the validity of the experimental design, posture entry methods software and training materials.

6.5.2 Subjects

A total of 11 subjects were used in this experiment. Ten of the eleven pilot subjects were engineering students. The 11th subject had no technical training. The subjects averaged 5-10 engineering courses, 1 year of industrial experience and 3-5 years of experience with computers. All subjects had no experience in the use of ergonomics software and only one subject had taken any courses in ergonomics. All subjects were volunteers who were paid $5 per hour for their time.

6.5.3 Method

In the pilot experiment, the methods were the same as described in Section 5.7. However, the pilot experiment differed from the main novice experiment (Chapter 6) because the view angles of the three dimensional graphic human form model were automatically set to the same perspective as used in the photographs. In addition, since the

pilot experiment was used to determine which sections of the training materials were in need of revision, the training materials changed from subject to subject.

6.5.4 Results

6.5.4.1 Accuracy. The mean accuracy of the three different posture entry methods is shown in Table 6.4. Accuracy is measured as the average difference between the measured and entered joint angles. There are four angles for the legs, three for the trunk and eight for the arms. The inverse kinematics group had a mean accuracy of 8.4 degrees, which is significantly better than the mean accuracy for the direct manipulation group (10.4 degrees) and the joint angle group (10.6 degrees). The results of the ANOVA analysis are shown in Table 6.5.

TABLE 6.4 *Mean and standard deviation differences (in degrees) between entered and measured joint angles*

	Posture:	Easy	Medium	Hard	Totals:
Method	Joint angle	6.7 (2.8)	12.1 (3.5)	12.8 (3.7)	10.6 (4.3)
	Direct manipulation	6.8 (2.5)	11.2 (4.8)	13.0 (7.9)	10.4 (6.0)
	Inverse kinematics	5.5 (1.5)	10.2 (3.5)	9.4 (2.8)	8.4 (3.4)
Totals:		6.3 (2.3)	11.1 (4.0)	11.7 (5.5)	9.7 (4.8)

TABLE 6.5 *ANOVA comparison of the mean difference between entered and measured joint angles*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	82	6.725	0.011	*
Inverse kinematics vs. Direct manipulation	1	82	6.485	0.013	*
Direct manipulation vs. Joint angle	1	82	0.056	0.814	

A table of accuracy values for the different parts of the body is shown in Table 6.6. The greatest difference between the three methods is the accuracy at the arms. The difference of 5 degrees can be of practical significance according to Chaffin and Erig (1991) because it can mean a 10% change in the accuracy of a biomechanical model. The results from an ANOVA which compared the mean difference between entered and measured joint angles at the arms is shown in Table 6.7.

TABLE 6.6 *Mean and standard deviation accuracy values for the different parts of the body (angles)*

	Legs	Trunk	Arms
Joint angle	3.9(2.7)	7.0(3.3)	15.3(7.6)
Easy	3.8(2.8)	5.2(2.5)	8.8(4.7)
Medium	3.5(2.3)	8.0(4.1)	18.0(5.8)
Hard	4.4(3.1)	7.7(2.9)	19.0(7.8)
Direct manipulation	4.1(3.0)	7.6(4.6)	14.6(10.5)
Easy	3.8(2.8)	5.0(3.7)	9.1(4.2)
Medium	3.3(1.2)	8.2(4.7)	16.4(8.1)
Hard	5.2(4.2)	9.7(4.3)	18.1(14.8)
Inverse kinematics	4.0(2.4)	6.6(4.0)	11.2(5.2)
Easy	3.8(3.0)	2.9(1.2)	7.3(2.5)
Medium	4.8(2.3)	7.8(3.0)	13.9(6.0)
Hard	3.4(1.8)	9.1(4.0)	12.5(4.0)

TABLE 6.7 *ANOVA comparison of the mean difference between entered and measured joint angles for the arms only*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	82	6.818	0.011	*
Inverse kinematics vs. Direct manipulation	1	82	5.366	0.023	*
Direct manipulation vs. Joint angle	1	82			

While the accuracy results for the inverse kinematics method were significantly better than the joint angle and direct manipulation methods from a statistical perspective, they were also significantly better in a practical sense. The Chaffin and Erig (1991) guideline stated that accuracy errors greater than 10° could cause a significant change in a

biomechanical analysis. In addition, errors greater than 15° would be considered major errors. Table 6.8 shows how the inverse kinematics method, while not always able to meet the Chaffin and Erig guideline, helped subjects to avoid making major mistakes, particularly at the arms.

TABLE 6.8 *Percentage of postures with accuracy errors of <10° and <15°*

	<10°			<15°		
Method	Legs	Trunk	Arms	Legs	Trunk	Arms
Joint angle	100%	89%	30%	100%	96%	48%
Direct manipulation	94%	72%	47%	100%	94%	67%
Inverse kinematics	100%	72%	47%	100%	97%	79%

6.5.4.2 Posture entry time. The mean posture entry times of the three different posture entry methods are shown in Table 6.9. The inverse kinematics method required 44% less posture entry time than the direct manipulation method and 73% less than the joint angle method. Such an improvement in posture entry time has practical significance since the amount of time required to perform an analysis was greatly reduced. Table 6.10 shows the results of the ANOVA analysis.

TABLE 6.9 *Mean and standard deviation posture entry times (seconds)*

	Posture:	Easy	Medium	Hard	Totals:
Method	Joint angle	549 (310)	563 (221)	728 (214)	614 (256)
	Direct manipulation	180 (102)	278 (143)	432 (408)	297 (270)
	Inverse kinematics	129 (64)	183 (104)	189 (109)	167 (96)
Totals:		262 (248)	321 (218)	424 (345)	336 (281)

TABLE 6.10 *ANOVA comparison of posture entry times for the three methods*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	82	71.814	<0.001	*
Inverse kinematics vs. Direct manipulation	1	82	7.066	0.009	*
Direct manipulation vs. Joint angle	1	82	36.159	<0.001	*

6.5.4.3 Accuracy as a function of time. An analysis of accuracy over time demonstrates the characteristics of each type of posture entry method. Subjects that used the inverse kinematics method quickly achieved a moderate accuracy level and only small adjustments were necessary at that point. However, subjects that used the other methods took a long time to achieve the same moderate level of accuracy. The graphs of accuracy over time were developed (Figures 6.2 - 6.4) based upon the model parameters shown in Table 6.11.

Each of the different methods were modeled by the following nonlinear equation (Neter, Wasserman, and Kutner, 1985) :

$$\theta = \beta_0 + \beta_1 * e^{\alpha * t}$$

where:

θ is the accuracy (in degrees)
β_0 is the asymptote
β_1 is the difference between θ at t=0 and β_0
α is the decay constant
t is time (in seconds)

The values for each of the three different methods is shown in Table 6.11. The low R^2 values are due to accuracy generally not showing gradual improvement, but rather fluctuating wildly as the subjects attempted to find the correct posture.

TABLE 6.11 *Nonlinear models of the three posture entry methods*

Method	Posture	β_0	β_1	α	R^2
Joint angle	Easy	7.741	12.150	-0.008	0.563
Joint angle	Medium	13.105	15.560	-0.006	0.417
Joint angle	Hard	13.987	20.474	-0.009	0.659
Direct manipulation	Easy	8.101	10.571	-0.020	0.510
Direct manipulation	Medium	9.516	19.238	-0.010	0.505
Direct manipulation	Hard	14.864	20.111	-0.017	0.291
Inverse kinematics	Easy	6.737	11.060	-6.419	0.921
Inverse kinematics	Medium	10.219	16.916	-0.064	0.785
Inverse kinematics	Hard	10.502	20.113	-0.057	0.824

Graphs of the nonlinear curves are shown in Figures 6.2, 6.3, and 6.4. Note that the graphs of the inverse kinematics group reach an asymptote much more quickly than the joint angle or direct manipulation group.

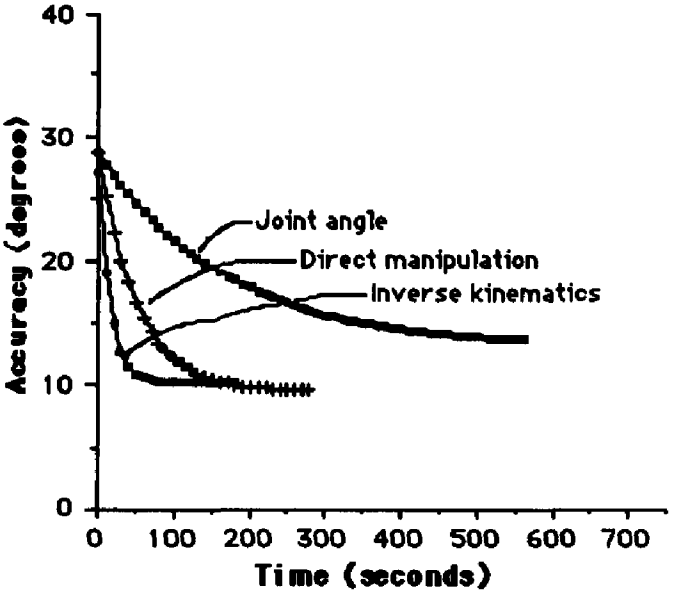


Figure 6.2 *Nonlinear models of easy postures*

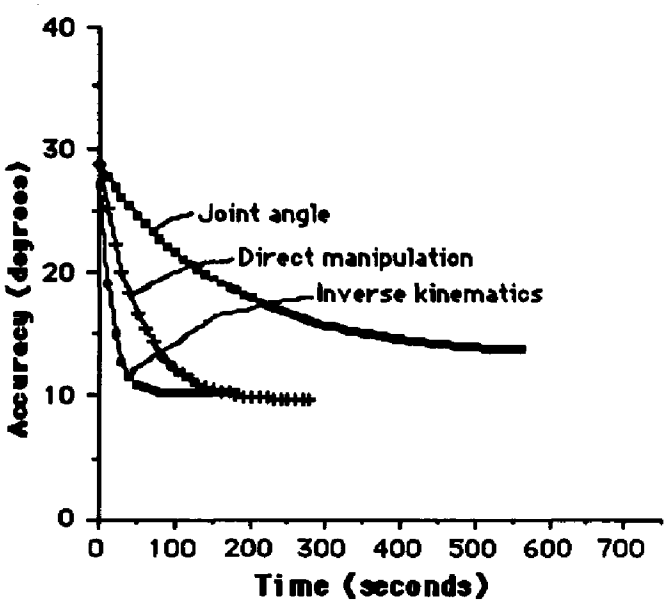


Figure 6.3 *Nonlinear models for medium postures*

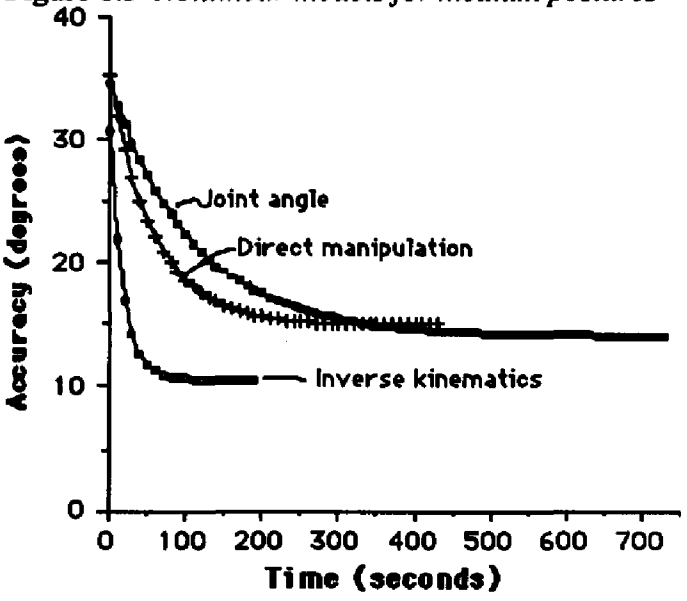


Figure 6.4 *Nonlinear models of hard postures*

6.5.4.4 Number of manipulations. There is a strong correlation between the number of posture manipulations and posture entry time within each of the three posture entry method groups as shown in Table 6.12.

TABLE 6.12 *Correlation between number of manipulations and posture entry time*

Method	Correlation
Joint angle	0.931
Direct manipulation	0.824
Inverse kinematics	0.797

Because of the strong correlation between number of manipulations and posture entry time, a comparison was made between the three posture entry methods. The resulting mean number of manipulations are in Table 6.13. In general, the number of manipulations were similar for the legs and the trunk. However, the inverse kinematics method required 62% fewer arm manipulations than the joint angle method and 67% less than the direct manipulation method. The results of the ANOVA analyses are in Tables 6.14 and 6.15.

TABLE 6.13 *Mean and standard deviation number of manipulations*

	Legs	Trunk	Arms	Total
Joint angle	3.0(2.1)	6.6(4.8)	23.3(12.6)	32.9(16.6)
Easy	3.8(2.6)	3.1(1.7)	17.0(8.2)	23.9(10.3)
Medium	2.3(2.1)	7.6(4.2)	20.4(9.4)	30.3(13.5)
Hard	3.0(1.2)	9.1(5.8)	32.3(14.7)	44.4(18.9)
Direct manipulation	2.1(3.0)	8.9(12.0)	26.3(21.5)	37.3(29.2)
Easy	3.3(3.3)	6.3(6.3)	14.4(5.5)	24.0(10.0)
Medium	0.7(1.5)	8.6(7.2)	24.8(12.2)	34.1(17.0)
Hard	2.5(3.4)	11.8(18.8)	39.6(30.6)	53.9(42.6)
Inverse kinematics	1.6(4.2)	5.2(4.7)	5.5(8.2)	12.4(12.0)
Easy	1.7(2.6)	2.5(2.4)	3.3(4.5)	7.0(5.6)
Medium	3.0(6.6)	5.4(3.8)	5.8(9.7)	14.2(14.6)
Hard	0.8(1.5)	7.8(5.9)	7.4(9.7)	15.9(12.8)

TABLE 6.14 *ANOVA comparison of the total number of manipulations for the three posture entry methods*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	82	16.771	<0.001	*
Inverse kinematics vs. Direct manipulation	1	82	28.956	<0.001	*
Direct manipulation vs. Joint angle	1	82	0.786	0.378	

TABLE 6.15 *ANOVA comparison of the number of arm manipulations for the three posture entry methods*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	82	38.971	<0.001	*
Inverse kinematics vs. Direct manipulation	1	82	24.403	<0.001	*
Direct manipulation vs. Joint angle	1	82			

6.5.4.5. Time per manipulation. In addition to the number of manipulations for each method, the amount of time per manipulation was analyzed. Two cases were deleted from the inverse kinematics method because the subjects chose not to manipulate the body after the initial inverse kinematics estimate. The means and standard deviations for all three posture entry methods is shown in Table 6.16. The direct manipulation method required significantly less time per manipulation than the joint angle and inverse kinematics methods. The results of the ANOVA analysis are shown in Table 6.17.

TABLE 6.16 *Mean and standard deviation time per manipulation (seconds)*

	Posture:	Easy	Medium	Hard	Totals:
Method	Joint angle	21.9 (5.7)	19.1 (4.3)	17.5 (4.5)	19.4 (5.0)
	Direct manipulation	7.3 (1.3)	8.3 (2.2)	7.5 (1.5)	7.7 (1.7)
	Inverse kinematics	18.7 (8.5)	15.0 (8.4)	10.3 (3.2)	14.6 (7.8)
Totals:		15.3 (8.6)	13.7 (7.1)	11.3 (5.1)	13.4 (7.2)

TABLE 6.17 *ANOVA comparison of the time per manipulation for the three posture entry methods*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	80	15.402	<0.001	*
Inverse kinematics vs. Direct manipulation	1	80	34.855	<0.001	*
Direct manipulation vs. Joint angle	1	80	91.250	<0.001	*

The difference in time per manipulation between the direct manipulation method and the inverse kinematics method was not affected by computation time. The maximum amount of time required to estimate a posture using the inverse kinematics algorithm outlined in Chapter 4 using a Vaxstation 3100 Model 38 is roughly 0.25 seconds.

6.5.4.6. Training time. Training time is defined as the time between the start of the training the time when the subject sucessfully entered the second practice posture. The training time for the joint angle group was found to be greater than the time for the direct manipulation group and inverse kinematics group, although this could not be statistically tested. In addition, the difference in training time between the inverse kinematics and direct manipulation groups was small. The training times for each of the different posture entry method groups is shown in Figure 6.5.

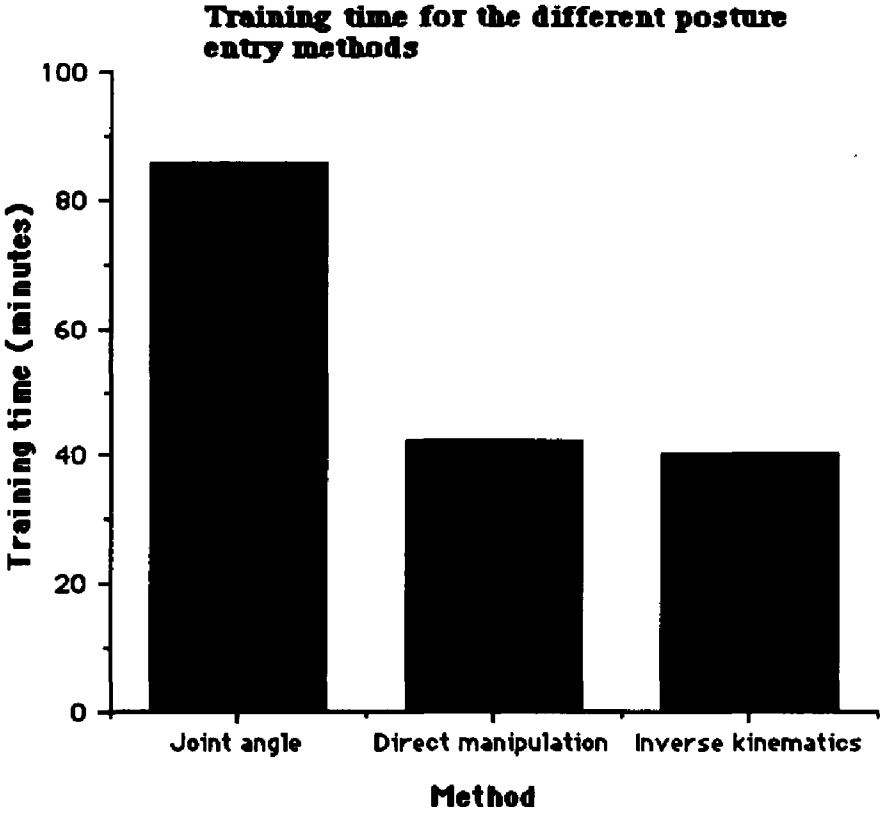


Figure 6.5 *A comparison of the training times for the different methods (in minutes)*

6.5.4.7 A comparison of easy, medium and hard postures In order to verify that the labelling of the easy, medium and hard postures was appropriate, an ANOVA analysis was used to compare the performance on the easy, medium and hard postures. As was stated in the Methods section, the easy postures were entered first, then the medium and finally the hard. The posture entry times are shown in Table 6.9, and the accuracy values are shown in Table 6.4. The graphs of posture entry time and accuracy for easy, medium, and hard postures are shown in Figures 6.6 and 6.7, respectively. The graphs indicate that the easy postures were the fastest to enter in terms of posture entry time and that the hard postures were the slowest to enter in terms of posture entry time. Similarly the easy postures were entered most accurately, and the hard postures were entered the least accurately. The results of the ANOVA analysis are shown in Tables 6.18 and 6.19, respectively.

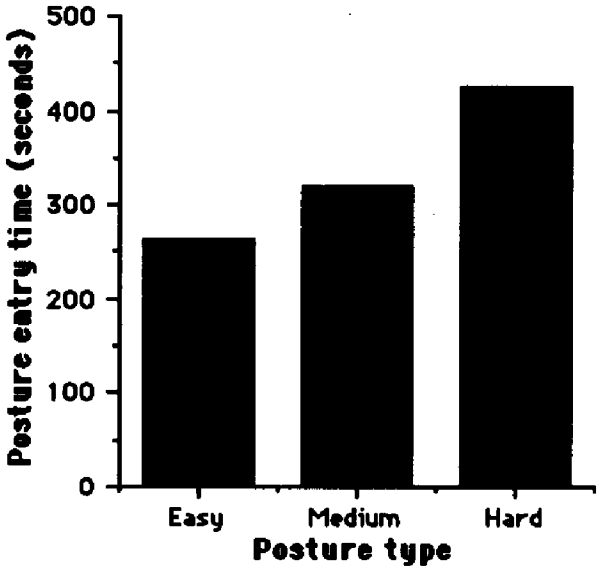


Figure 6.6 *Posture entry time for different posture types*

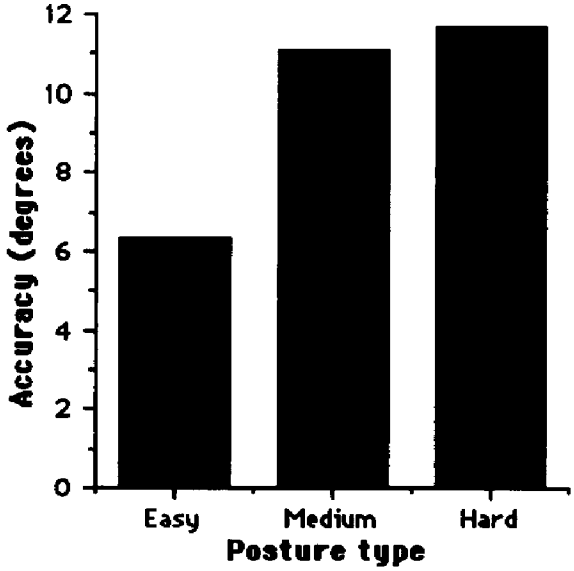


Figure 6.7 *Accuracy for different posture types*

TABLE 6.18 *ANOVA comparison of the posture entry time for easy, medium and hard postures*

Comparison	DF	DF_{error}	F	p	Significant
Easy postures vs. Medium postures	1	82	1.160	0.285	
Easy postures vs. Hard postures	1	82	10.100	0.002	*
Medium postures vs. Hard postures	1	82	4.414	0.039	*

TABLE 6.19 *ANOVA comparison of the accuracy for easy, medium and hard postures*

Comparison	DF	DF_{error}	F	p	Significant
Easy postures vs. Medium postures	1	82	34.102	<0.001	*
Easy postures vs. Hard postures	1	82	42.099	<0.001	*
Medium postures vs. Hard postures	1	82	0.431	0.531	

6.5.5 Changes in the training manuals during the pilot experiment

Because of the difficulties encountered by the subjects in the pilot experiment, several changes were made in the training manuals. The changes were as follows;

1. Additional text and diagrams describing horizontal arm angles were added.
2. The instructions for selecting hand locations by direct manipulation were reworded.
3. The final paragraph of the training manuals were reworded to more clearly state that the subjects should emphasize attaining the Chaffin and Erig guidelines when entering postures.

These changes were significant because it meant that all subjects did not use the same training materials. The first few subjects in each group were hampered by the lack of clarity and poor wording of some portions of the manual. Therefore, comparisons across groups cannot be considered significant based upon this study.

6.5.6 Evaluation of hypotheses based upon pilot experiment

Significant effects due to posture entry method were found for posture entry time, accuracy, number of manipulations, and time per manipulation. Based upon these results, the experimental design appears to be adequate to determine statistically significant differences between methods. However, since the training manuals were significantly

revised during the pilot experiment, then these results cannot be generalized. The experiment was repeated (Chapter 7) using the user view selection (as opposed to automatic view selection) and the final version of the manuals.

While there were no hypotheses concerning the easy, medium, and hard postures, the pilot experiment demonstrated there were significant differences in performance depending upon the type of posture. Hence, the initial characterizations of "easy", "medium", and "hard" postures appear to be appropriate.

6.5.7 Pilot experiment conclusions

The primary conclusion that can be drawn from the pilot experiment is that the experimental design and methods are acceptable for determining significant differences between the three posture entry methods. In addition, the pilot experiment demonstrated significantly better performance for subjects who used the inverse kinematics method, particularly in terms of posture entry time. While this result is confounded by the changes in the training materials, it does support the thesis statement of this research.

CHAPTER VII

NOVICE POSTURE ENTRY METHODS EXPERIMENT

7.1 Introduction

The purpose of the novice posture entry methods experiment was to compare the performance of novice users of the inverse kinematics, direct manipulation, and joint angle methods. This experiment was necessary because the changes in the training materials confounded the results of the pilot experiment. Another difference from the pilot experiment was that the subjects were required to set the view angle of the graphic human form model to the same as the photographs themselves, thus mental image rotation was needed.

The results showed that the inverse kinematics method required the least posture entry time and was the most accurate of the three methods. The primary reason that this is true is because the inverse kinematics algorithm predicts moderately accurate postures which minimize the number of posture adjustments that the user is required to make.

7.2 Method

The procedures and equipment used in this experiment were the same as the pilot experiment with the exception that the view angle of the graphic human form model was not automatically set to the same as the photographs, thus mental image rotation was necessary. The initial view was a front view and the subjects altered this view to match the photographs. While the training materials encouraged the subjects to alter the view of the graphic human form model, they were not required to do so. The training materials were

the same as used in the pilot experiment with an additional section which described how to alter the view of the graphic human form model.

7.3 Subjects

A total of 21 engineering students participated in the experiment. All subjects were volunteers who were paid $5 per hour for their time. The subjects were randomly assigned to the three groups with the exception that the six graduate students were divided evenly. The average backgrounds of the subjects are shown in Table 7.1. None of the subjects had any industrial experience in ergonomics or had used any software that included posture entry. In addition, no subjects had ever taken any courses in ergonomics.

TABLE 7.1 Subject backgrounds

Major	Aerospace Engineering - 1 Computer Engineering - 2 Electrical Engineering - 5 Industrial Engineering - 1 Mechanical Engineering - 4	Chemical Engineering - 2 Computer Science - 2 Engineering Physics - 1 Materials Engineering - 2 Operations Research - 1

Engineering courses	5-10 courses
Non engineering technical courses	More than 10 courses
Years of experience with computers	3-5 years
Years of experience with pointing devices	1-2 years
Ergonomics courses	0 courses
Industrial experience in ergonomics	0 years

One subject in the joint angle method entered three easy postures and one medium posture and then asked to leave the experiment. At this point, the experiment had lasted four hours. In order for the design to remain balanced, an additional subject was included in joint angle method group.

7.4 Novice Experiment Results

7.4.2 Accuracy

The accuracy of the three posture entry methods is shown in Table 7.2. Research by Chaffin and Erig (1991), which was mentioned previously, demonstrated than an error of ten degrees at a single joint could cause a significant change in biomechanical stress indicators. Notice that all three methods have approximately the same accuracy for easy and medium postures. However, the inverse kinematics method (~8.8°) is significantly more accurate than the direct manipulation method (~12.3°) and the joint angle method (~11.0°) for the hard postures. The ANOVA results are shown in Table 7.3. According to Chaffin and Erig (1991), the difference of 2.5 degrees can have a slight impact (plus or minus 5%) on a biomechanical strength analysis.

TABLE 7.2 *Mean and standard deviation differences between entered and measured joint angles (degrees)*

	Posture:	Easy	Medium	Hard	Totals:
Method	Joint angle	6.6 (2.9)	10.2 (2.6)	11.0 (3.7)	9.3 (3.6)
	Direct manipulation	6.5 (2.4)	8.8 (2.5)	12.3 (3.2)	9.2 (3.6)
	Inverse kinematics	6.8 (2.0)	9.1 (1.9)	8.8 (2.5)	8.2 (2.3)
Totals:		6.6 (2.4)	9.4 (2.4)	10.7 (3.4)	8.9 (3.3)

TABLE 7.3 *ANOVA comparison of the mean difference between entered and measured joint angles for hard postures only*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	42	5.4	0.024	*
Inverse kinematics vs. Direct manipulation	1	42	13.4	0.001	*
Direct manipulation vs. Joint angle	1	42	1.8	0.191	

There also was a significant difference in performance between subjects ($F(18,162)=1.8$, $p=0.028$). This is not surprising since there are significant differences in the abilities of people to perceive the shapes and features of unfamiliar objects (Wickens, 1984) and perform mental image rotation.

There were no significant differences in the accuracy of positioning for the three different sections of the body (i.e., the arms, torso and legs). This contrasts with the pilot experiment in which the inverse kinematics method was significantly more accurate for the arm postures than the other two methods. However, if only hard postures are considered, then the inverse kinematics method was more accurate for arm postures than the direct manipulation method and the joint angle method. Table 7.4 shows the accuracy values for the different sections of the body and Table 7.5 shows the results of the ANOVA analysis.

TABLE 7.4 *Mean and standard deviation accuracy values for the different parts of the body (degrees)*

	Legs	Trunk	Arms
Joint angle	3.8(2.9)	6.9(3.9)	12.9(5.7)
Easy	3.6(3.4)	4.3(2.5)	8.9(4.7)
Medium	3.0(1.3)	8.4(3.3)	14.5(4.4)
Hard	4.8(3.4)	8.0(4.5)	**15.3**(5.8)
Direct manipulation	4.5(3.4)	6.9(4.4)	12.1(5.7)
Easy	3.9(2.5)	4.3(1.7)	8.6(4.1)
Medium	3.7(2.0)	7.5(3.0)	11.8(4.6)
Hard	5.8(4.8)	11.0(4.9)	**16.0**(5.8)
Inverse kinematics	4.2(3.3)	6.4(2.8)	11.0(4.1)
Easy	4.2(2.3)	4.7(1.9)	9.0(3.5)
Medium	3.2(2.8)	6.9(2.3)	12.8(3.3)
Hard	5.3(4.4)	7.6(3.2)	**11.1**(4.6)

TABLE 7.5 *ANOVA comparison of the mean difference between entered and measured arm angles for hard postures only*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	42	8.2	0.007	*
Inverse kinematics vs. Direct manipulation	1	42	5.9	0.019	*
Direct manipulation vs. Joint angle	1	42	0.2	0.667	

Part of the difference in the accuracy of the arm angles for hard postures is due to one arm being hidden by other parts of the body in the photographs. An analysis was performed to determine the difference in accuracy between the hidden arm and the visible arm. The results are shown in Table 7.6. The accuracy for the inverse kinematics group does not vary much between the hidden arm and visible arm. However, there is a significant difference in the accuracy for the joint angle and direct manipulation groups.

TABLE 7.6 *Comparison of accuracy for hidden arm vs. visible arm for hard postures*

Method	Hidden arm	Visible arm
Joint angle	16.7(10.7)	13.8(8.5)
Direct manipulation	17.6(8.0)	14.3(8.3)
Inverse kinematics	10.4(6.1)	11.8(5.9)

Similar to the pilot experiment, the accuracy errors were evaluated to determine the percentage which were less than 10° and less than 15°. These results, shown in Table 7.7, indicate that the inverse kinematics method aided subjects such that they did not commit major errors. This is particularly true for arm postures. This demonstrates that in addition to the statistically significant differences, the inverse kinematics method led to a practical improvement in accuracy.

TABLE 7.7 *Percentage of postures with accuracy errors of <10° and <15°*

	<10°			<15°		
Method	Legs	Trunk	Arms	Legs	Trunk	Arms
Joint angle	95%	76%	37%	100%	95%	65%
Direct manipulation	89%	75%	43%	98%	92%	70%
Inverse kinematics	94%	87%	43%	98%	100%	84%

7.4.2 Posture entry time

The mean posture entry time for the three different posture entry methods is shown in Table 7.8. These values represent the time required from the moment that the subject was provided with the photograph to the moment when the subject exited the program. The inverse kinematics method (338 seconds) required 48% less posture entry time than the direct manipulation method (649 seconds) and 57% less than the joint angle method (798 seconds). The results of the ANOVA analysis are shown in Table 7.9.

TABLE 7.8 *Mean and standard deviation posture entry times (seconds)*

	posture:	Easy	Medium	Hard	Totals:
method	Joint angle	584 (242)	945 (438)	867 (471)	798 (420)
	Direct manipulation	417 (175)	772 (389)	757 (473)	649 (398)
	Inverse kinematics	267 (106)	356 (182)	390 (176)	338 (164)
Totals:		423 (222)	691 (428)	671 (443)	595 (395)

TABLE 7.9 *ANOVA comparison of the mean posture entry time*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	162	76.4	<0.001	*
Inverse kinematics vs. Direct manipulation	1	162	34.8	<0.001	*
Direct manipulation vs. Joint angle	1	162	8.1	0.005	*

The posture entry time includes more than strictly the time that the subjects spent manipulating postures. All three groups spent time entering the view angles, and the inverse kinematics group was required to spend time typing in the hand locations. The relative amount of time spent on each task is shown in Figure 7.1.

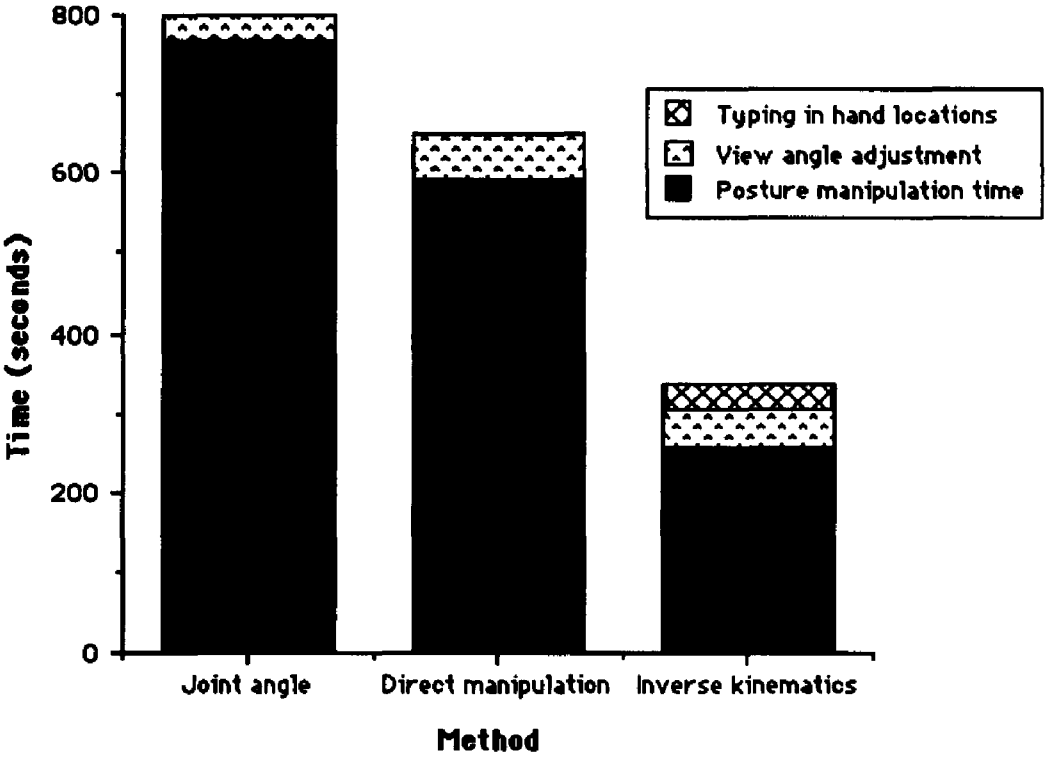


Figure 7.1 *Description of time spent on different tasks while entering postures*

7.4.3 Accuracy as a function of time

Each of the different methods was modeled by the same nonlinear equation used in Section 6.7.4.3 using the BMDP™ statistical software (Dixon, Brown, Engelman, Frane, Hill, Jennrich, and Toperek, 1981). The values for each of the variables is shown in Table

7.10. The low R^2 values are due to the fact that the accuracy did not show gradual improvement, but rather it fluctuated wildly as it did in the pilot experiment. Graphs of each of the nonlinear regression curves are shown in Figure 7.2.

TABLE 7.10 *Nonlinear models of the three posture entry methods*

Method	Posture	β_0	β_1	α	R^2
Joint angle	Easy	6.55	13.33	-0.004	0.435
Joint angle	Medium	13.20	16.88	-0.005	0.414
Joint angle	Hard	12.67	19.69	-0.004	0.596
Direct manipulation	Easy	8.17	11.05	-0.006	0.293
Direct manipulation	Medium	11.70	21.05	-0.006	0.363
Direct manipulation	Hard	11.81	24.70	-0.005	0.641
Inverse kinematics	Easy	5.67	9.95	-0.007	0.512
Inverse kinematics	Medium	11.18	14.84	-0.027	0.371
Inverse kinematics	Hard	11.17	18.46	-0.045	0.320

7.4.5 Number of manipulations

The number of manipulations required for each method is shown in Table 7.11. Each time that a subject altered the position of a body segment is considered a manipulation. This data reveals how often the subjects changed the posture of each section of the body before deciding that the whole-body posture was accurate enough. The results of the ANOVA analysis are shown in Table 7.12.

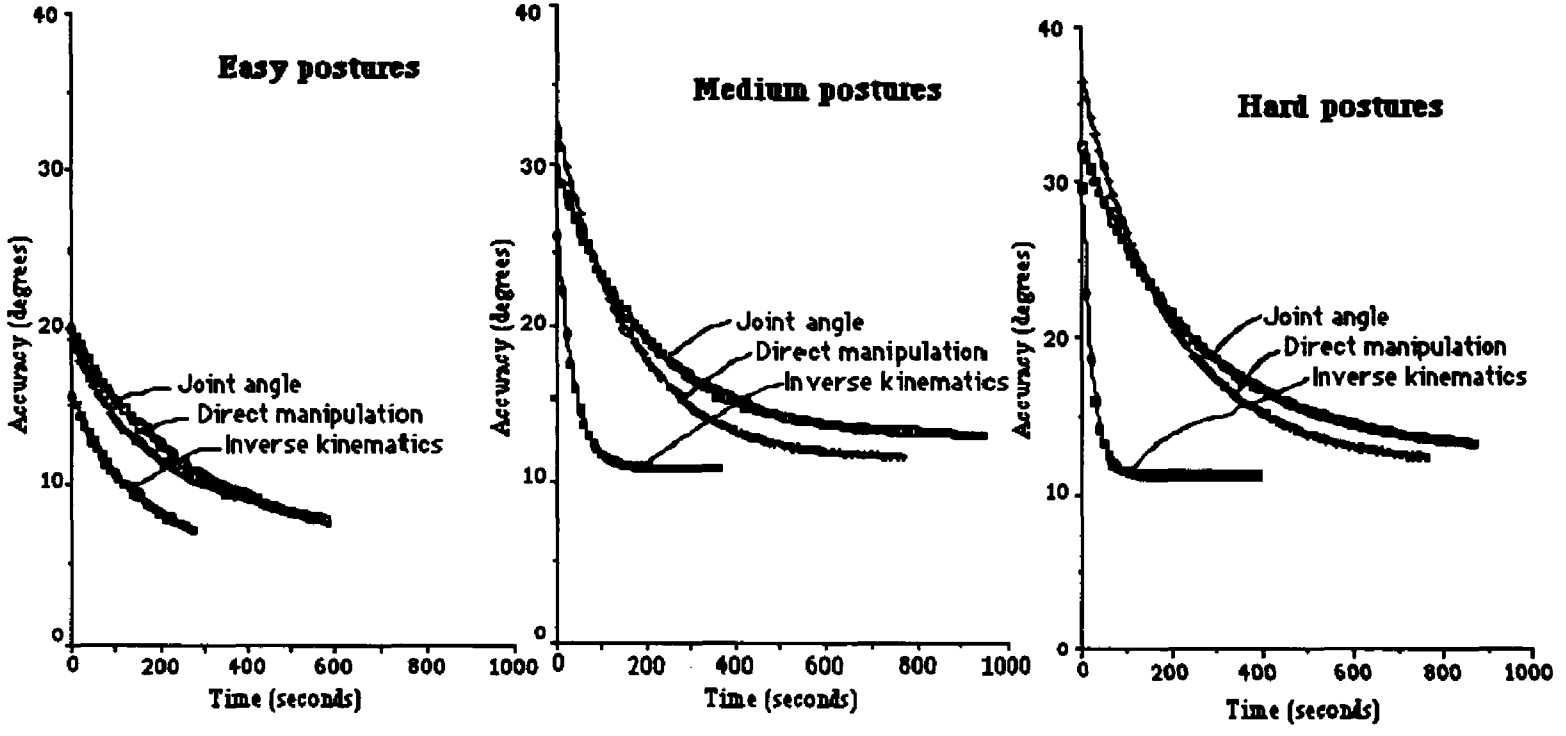


Figure 7.2 Nonlinear models of accuracy as a function of time (within trials)

TABLE 7.11 *Mean and standard deviation number of manipulations*

	Legs	Trunk	Arms	Total
Joint angle	2.3(2.6)	9.0(8.2)	**39.0**(31.0)	50.3(34.9)
Easy	2.4(2.4)	6.1(4.9)	**22.9**(12.1)	31.4(13.1)
Medium	1.7(2.3)	11.7(11.1)	**48.2**(7.4)	61.5(38.7)
Hard	2.9(3.1)	9.2(6.7)	**45.8**(35.8)	57.9(39.1)
Direct manipulation	5.5(6.1)	13.2(12.8)	**44.8**(35.5)	63.5(45.2)
Easy	5.4(5.5)	5.6(2.8)	**23.7**(14.7)	34.8(17.3)
Medium	3.7(5.2)	15.5(10.6)	**55.7**(37.6)	74.9(44.1)
Hard	7.4(7.0)	18.5(17.0)	**44.8**(39.6)	81.0(52.7)
Inverse kinematics	3.9(6.9)	13.1(12.0)	**12.8**(10.2)	29.8(21.8)
Easy	5.3(10.3)	7.0(5.6)	**9.0**(4.2)	21.3(17.3)
Medium	2.4(3.9)	13.6(10.2)	**12.2**(10.3)	28.2(19.2)
Hard	4.0(4.8)	18.8(15.4)	**17.0**(13.0)	39.8(25.0)

TABLE 7.12 *ANOVA comparison of the mean number of manipulations*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	162	42.2	<0.001	*
Inverse kinematics vs. Direct manipulation	1	162	15.6	<0.001	*
Direct manipulation vs. Joint angle	1	162	6.5	0.011	*

While the inverse kinematics method (29.8 manipulations) required fewer total manipulations than the direct manipulation method (63.5 manipulations) and the joint angle method (50.3 manipulations), this difference is due strictly to the number of arm manipulations. The difference in the number of manipulations between the inverse kinematics method and the other methods at the arms is so large that it makes the difference in the total number of manipulations significant.

7.4.6 Time per manipulation

A similar analysis was also performed for the amount of time required per manipulation. Table 7.13 shows the time per manipulation data for easy, medium and hard

postures. The time per manipulation was calculated on a posture by posture basis by dividing the amount of time by the number of manipulations. The direct manipulation method (11.5 seconds) required significantly less time per manipulation than the joint angle method (17.4 seconds) and the inverse kinematics method (13.8 seconds). The inverse kinematics method required significantly less time than the joint angle method. The results of the ANOVA analysis is shown in Table 7.14.

TABLE 7.13 *Mean and standard deviation time per manipulation (seconds)*

	posture:	Easy	Medium	Hard	Totals:
method	Joint angle	19.3 (4.9)	16.6 (4.3)	16.3 (4.2)	17.4 (4.6)
	Direct manipulation	12.8 (4.3)	11.4 (3.6)	10.4 (3.2)	11.5 (3.6)
	Inverse kinematics	14.7 (4.2)	16.1 (12.4)	10.5 (3.7)	13.8 (9.1)
Totals:		15.6 (4.6)	14.7 (8.1)	12.4 (4.6)	14.2 (6.7)

TABLE 7.14 *ANOVA comparison of the mean time per manipulation*

Comparison	DF	DF_{error}	F	p	Significant
Inverse kinematics vs. Joint angle	1	162	15.6	<0.001	*
Inverse kinematics vs. Direct manipulation	1	162	6.3	0.013	*
Direct manipulation vs. Joint angle	1	162	41.9	<0.001	*

7.4.7 Training time

The amount of time spent in training is shown in Table 7.15. The training time begins when the experimenter begins reading the training documentation aloud and ends when the second practice posture has been successfully entered. The differences between

each method were small but could not be compared statistically. Each required about 70 minutes with a standard deviation of about 10 minutes.

TABLE 7.15 *Mean and standard deviation training times for the three methods (minutes)*

	Training time (minutes)
Joint angle	75(11)
Direct manipulation	68(7)
Inverse kinematics	70(12)

7.4.8 Three dimensional graphic human form orientation

In this experiment the subjects selected the orientation of the three dimensional graphic human form to represent the perspective of the photographs. Because the orientation was not automatically set, the three dimensional view could potentially be misleading and reduce the accuracy of the posture. However, the training stressed the importance of the three dimensional graphic human form orientation.

The problem of entering the correct view angle is demonstrated in Figures 7.3 and 7.4. The three graphic human forms shown in Figure 7.4 all depict the posture of the worker shown in Figure 7.3, but from different viewing angles. Notice that only the leftmost posture can readily be identified as matching the worker in the photograph.

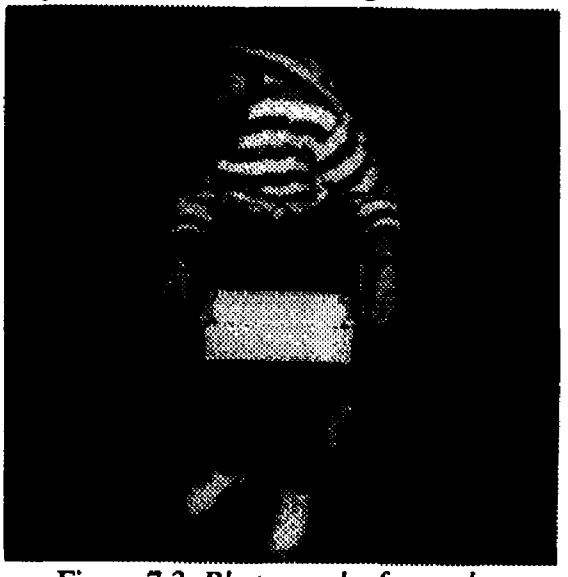


Figure 7.3 *Photograph of a worker*

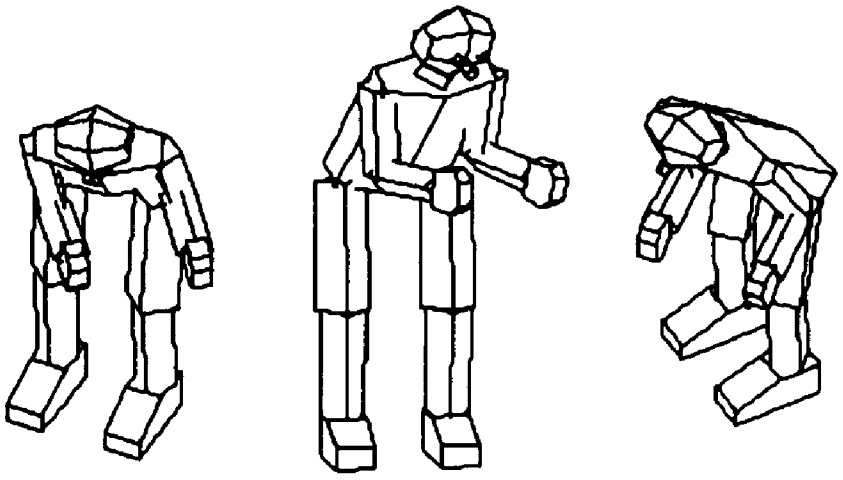


Figure 7.4 *Three views of the worker's posture shown in Figure 7.3*

In order to test the hypothesis that the view angle of the three dimensional graphic human form affects posture accuracy, average view angle data were collected. The average view angle error is defined as the average difference between the entered and actual view angles determined from the position of the camera used in taking the photographs viewed by the subjects. In addition, a correlation analysis was run to determine the effect of orientation on posture accuracy. These data are shown in Table 7.16.

TABLE 7.16 *Three dimensional graphic human form view angle accuracy*

Method	Average error (degrees)	Standard deviation	Correlation to accuracy
Joint angle	8.6	4.4	-0.202
Direct manipulation	10.2	5.4	-0.125
Inverse kinematics	13.5	12.3	-0.259

The subjects were able to enter the view angle of the graphic human form model very accurately, as shown in Figure 7.5. In 75% of the trials, the average view angle error was 13 degrees or less, and in 33% of the trials, the average view angle error was 7.5 degrees or less.

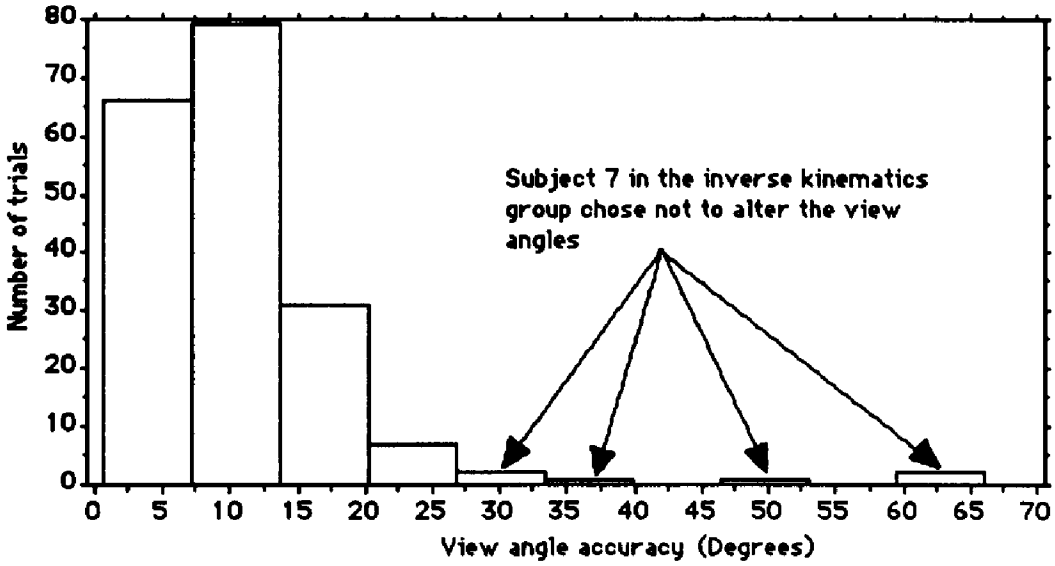


Figure 7.5 *Histogram of view angle accuracy data*

While subjects were able to enter the view angles accurately, the task of altering the view angles also increased significantly as evidenced by the increase in posture entry time from the pilot experiment to the main experiment. Therefore, while altering the view angle may have been beneficial, there was also an associated time penalty. Subject 7, in fact, elected to disregard the graphic human form model and use the three orthogonal views of the stick figures to select postures. The reason the subject used the three orthogonal views was because of his familiarity with Computer Aided Design systems that use orthogonal views. The postures entered by this subject were extremely accurate and the posture entry time was close to the mean for the inverse kinematics method.

A surprising result was the subjects who used the inverse kinematics method entered the orientations less accurately than the joint angle subjects and the direct manipulation subjects. However, even though the difference is statistically significant, it is not a large difference in terms of viewing angle. The average difference between the joint

angle and inverse kinematics methods is only five degrees, which makes relatively little difference in the perspective of the three dimensional graphic human form.

7.4.9 Post experimental survey

After completing the experiment, each of the subjects was asked to fill out a post experiment survey. The first question asked the subjects to rate how enjoyable the software was. For purposes of comparison, the subject's favorite computer game and the worst software they had used were the anchors. A Kruskal-Wallis nonparametric test was used to determine that there were no detectable significant differences in the preferences between the three groups (p=0.440). The average ratings for each group (1=like your favorite computer game and 5=like the worst software you have ever used) are shown in Table 7.17.

TABLE 7.17 *Subjective ratings*

Method	Average rating	Standard deviation
Joint angle	3.0	1.0
Direct manipulation	2.4	0.8
Inverse kinematics	2.6	0.5

The second question on the post experiment survey asked which part of the body was the hardest to enter. Table 7.18 contains the responses, which show that the subjects who used the direct manipulation and joint angle methods had the most difficulty in manipulating the arms. This was not the case for the inverse kinematics subjects, since more than half felt that manipulating the trunk was harder than the arms. The reason for this result is the inverse kinematics algorithm made manipulating the arms to be easier. The third alternative was the legs, but no subjects considered this part of the body to be the hardest to enter.

TABLE 7.18 *Hardest part of the body to enter*

Method	Number choosing arms	Number choosing trunk
Joint angle	6	1
Direct manipulation	5	2
Inverse kinematics	3	4

7.4.10 Comparison to NGOMSL analysis

A comparison was made to the NGOMSL analysis in order to determine the value of the R operator. The R operator describes the task of converting a position in three dimensional space into a posture manipulation. Table 7.19 shows the values of R for the three posture entry methods.

TABLE 7.19 *R operator estimates (All time values in seconds)*

	Average time per manipulation	NGOMSL time per manipulation without R	Estimated R value
Joint angle	17.4	4.2	13.2
Direct manipulation	11.5	5.1	6.4
Inverse kinematics	13.8	5.1	8.7

The NGOMSL analysis assumed optimal behavior, which is why the number of manipulations predicted for each method was a minimum. However, the number of manipulations for each method was considerably higher than those values, which implies that the subjects tried a number of different postures. The iterative strategy used by the subjects explains why the NGOMSL time predictions were substantially less than the observed time. A comparison of the number of predicted and observed number of manipulations is shown in Table 7.20.

The NGOMSL model helps to explain why the subjects who used the joint angle and direct manipulation methods required more posture manipulations than the subjects who used the inverse kinematics method. Since the inverse kinematics algorithm automatically places the hands in the correct locations, this reduces the number of arm manipulations by a factor of two. However, this does not completely explain the difference in arm manipulations because the joint angle and direct manipulation subjects required over three times more arm manipulations than the inverse kinematics subjects. The additional reduction in arm manipulations for the inverse kinematics subjects was likely a result of the inverse kinematics algorithm predicting reasonable first approximates for the arm postures.

If the assumption had been made that a large number of manipulations were necessary, then the NGOMSL analysis would have predicted some of the posture entry time differences, since the model revealed that the inverse kinematics subjects required fewer arm manipulations than the other methods. Therefore, although the NGOMSL model was not used predictively, it could have been used to predict that the inverse kinematics method was the most efficient. However, it should be noted that the NGOMSL model could not predict the accuracy differences between the methods.

TABLE 7.20 *Comparison of predicted and observed number of manipulations*

	Predicted number of manipulations	Observed number of manipulations
Joint angle	15	50
Direct manipulation	15	64
Inverse kinematics	10	30

7.4.12 Qualitative feedback

Through informal discussions with the subjects during the rest periods, two of the joint angle subjects and two of the direct manipulation subjects revealed that they had finalized one posture in a trial prematurely. The reason for this was frustration. These four subjects reported frustration only for the medium and hard postures. The other ten subjects, while they may have been frustrated while entering postures, did not admit that this affected their accuracy. The main cause of frustration was the difficulties in getting the hands into the correct locations. The reason that positioning the hands correctly was so difficult was because a posture manipulation always changed two of the three coordinates of the hands (such as horizontal and vertical). This meant that positioning the hands by either direct manipulation or joint angle entry methods was a difficult problem solving task which resulted in occasional frustration.

The one subject in the joint angle method who left early reported extreme frustration with three of the four postures that were entered. The four postures included three easy postures and one medium posture. The subject did not attempt to enter any of the hard postures. After averaging 20 minutes per posture the subject asked to leave the experiment.

None of the subjects in the inverse kinematics method reported any frustration, although most felt that some of the postures were difficult to perceive.

7.5 Evaluation of testable hypotheses

The testable hypotheses were evaluated based upon the results reported in Section 7.4. The results are listed in Table 7.21.

TABLE 7.21 *Evaluation of testable hypotheses for novice subjects*

Posture entry time
1,2. The inverse kinematics method requires significantly less posture entry time than the direct manipulation method and the joint angle method
3. The direct manipulation method requires significantly less posture entry time than the joint angle method

Accuracy
4,5. The inverse kinematics method is significantly more accurate than the direct manipulation method and the joint angle method for hard postures
6. There is no detectable significant difference in accuracy between the direct manipulation and joint angle methods

Number of manipulations
7,8. The inverse kinematics method requires significantly fewer manipulations than the direct manipulation method and the joint angle method
9. The direct manipulation method requires significantly fewer manipulations than the joint angle method

Time per manipulation
10,12. The direct manipulation method requires significantly less time per manipulation than the inverse kinematics method and the joint angle method
11. The inverse kinematics method requires significantly less time per manipulation than the joint angle method

7.6 Discussion of Novice Experiment Results

The performance of the subjects in this experiment demonstrates that perceiving three dimensional postures from photographs is a very difficult task for novices. The reason for this is because the subjects were not able to enter postures correctly on the first try and a considerable number of adjustments were required to achieve what they believed to be the correct posture. This implies that the initial posture estimates were almost always wrong and that an iterative approach was required.

Despite the trouble that the subjects had in entering the postures, all three groups were able to enter postures which were more accurate than the inverse kinematics algorithm first predicted. The inverse kinematics algorithm by itself averaged 14 degrees of deviation per joint from the actual posture. This is five degrees higher than the manual

posture entry methods which averaged about 9 degrees. Therefore, while the manipulation methods are not perfect, they provided a means to greatly improve upon the initial posture prediction. The inverse kinematics algorithm would have to be substantially improved to match the accuracy of the manual posture entry methods. However, it should be noted that the accuracy of the inverse kinematics algorithm is quite good, considering how quickly postures can be predicted (<30 seconds with the time to type in the hand locations included). Because of the long posture entry times in general, the inverse kinematics algorithm is extremely useful, and serves as a baseline upon which other manual manipulation methods can now be judged.

The results of the experiment demonstrated that the inverse kinematics method is superior in terms of posture entry time to the other posture entry methods. The difference between the inverse kinematics method and the direct manipulation is particularly interesting because the only significant difference between the interfaces is the inverse kinematics algorithm. Despite the similarities, the inverse kinematics method required slightly more than half the posture entry time of the direct manipulation method. This decrease in posture entry time is due strictly to the posture manipulation time as shown in Figure 7.1.

The probable reason for the superiority of the inverse kinematics method over the direct manipulation method in terms of posture entry time is that the inverse kinematics algorithm always predicted a reasonable posture and maintained the hands in the correct positions for each manipulation of the joints. This meant that further adjustments tended to be minor which minimize the total number of manipulations. Furthermore, the inverse kinematics algorithm insured that the hands were always in the correct locations which more clearly showed the effects of manipulating the body. For example, when the subjects manipulated the trunk using the direct manipulation method, the only way to tell how this affected the arms was to manipulate the arms directly. However, when the subjects

manipulated the trunk using the inverse kinematics method the arms were automatically adjusted to maintain the desired hand positions. This showed how the trunk manipulation could impact the arm postures, and resulted in the substantial reduction in the number of arm manipulations.

The inverse kinematics method was also more accurate than the direct manipulation method for hard postures, which is harder to explain since all subjects entered postures based upon the same photographs. If perceptual ability did not vary significantly between groups, then there is no reason why the direct manipulation subjects could not have had the same accuracy as the inverse kinematics method subjects. One possibility is that when using direct manipulation the subjects did not spend sufficient time to be able to reach the required accuracy for the hard postures. Evidence for this hypotheses is supplied by the nonlinear regression curves of accuracy versus time shown earlier in Figure 7.2. Notice that the curve for the inverse kinematics method group reaches the asymptote fairly quickly and then has a long flat region but the curve for the direct manipulation method does not quite reach an asymptote. This implies that the direct manipulation subjects did not work long enough and could have achieved better accuracy if they had spent more time. However, the subjects were unwilling to spend more time because they were spending approximately 13 minutes per posture. Frustration and fatigue caused the subjects to be willing to accept lower accuracy. Recall, two of the direct manipulation subjects admitted to quitting early due to frustration when using this method.

A second reason for the better accuracy of the inverse kinematics method for the hard postures was that the inverse kinematics algorithm suggested alternatives that the subjects might not have thought of (some lateral bending of the torso, for example). The fact that the inverse kinematics method was significantly more accurate than the other methods at the arms supports this hypothesis because the arms have the most degrees of freedom. Whenever the number of posture alternatives is high, users can benefit from

suggestions, as provided by the inverse kinematics algorithm. These suggestions are particularly useful when one of the arms is hidden, as shown in Table 7.6. It should be noted that once a user positions the trunk correctly, the inverse kinematics algorithm can predict the arm locations quite accurately, since the end points (the shoulders and hands) are fixed and Kilpatrick's equations are used to calculate the position of the elbow with only one degree of freedom.

Another factor that should be considered is manipulating a single joint often necessitates manipulating other joints as well, which can affect the overall accuracy. An example is shown in Figure 7.6. Because of the large number of manipulations, the possibility exists that the subjects using the joint angle and the direct manipulation methods did not carefully consider how the other joints were affected. The subjects who used the inverse kinematics method were at an advantage since the algorithm predicted the positions of the joints between the one manipulated and the hands. This also implies that the inverse kinematics algorithm needs to be as accurate as possible, since subjects will sometimes fail to verify that the predictions are correct.

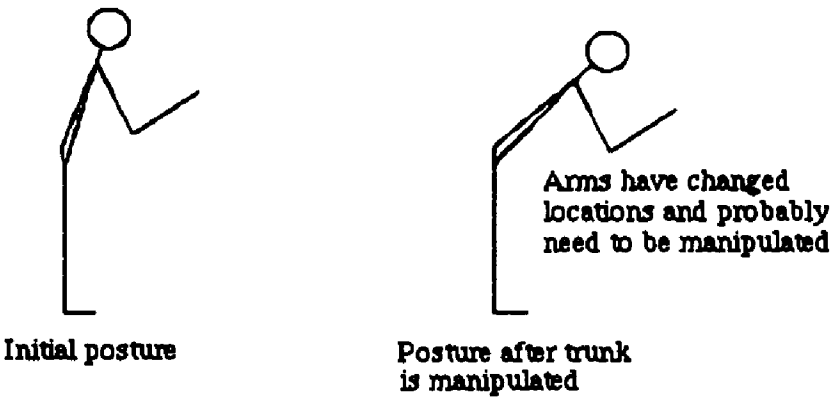


Figure 7.6 *Example of a posture manipulation that requires other joints to be altered*

Using the joint angle method required more posture entry time than direct manipulation. This affect method likely results from the addition of time required to perform mental image rotation. In order to estimate the joint angles the subjects had to be able to rotate the body segments in their minds about the vertical or horizontal planes. Similar to Barfield et al. (1988), extra time was required to perform mental image rotation. The high value of the R operator was further evidence of the how difficult it was to estimate joint angles. This implies that a large amount of time was required to convert segment positions in space into joint angles.

A difficult result to explain is why the direct manipulation subjects did not have better accuracy than the joint angle subjects, despite the significantly larger number of manipulations. One possible explanation is that the amount of information to be processed is so great that subjects make mistakes easily. Extra manipulations do not always improve accuracy, since the final posture for most trials was worse than one of the intermediate postures. This means that the only reliable way to improve accuracy is to have an inverse kinematics algorithm to aid in the selection of postures.

The average accuracy and posture entry time for the inverse kinematics method were reasonable considering that the subjects were novices with only 70 minutes of training. The average overall accuracy was below the ten degrees desired by Chaffin and Erig (1991), although the accuracy for the arms often was not. If the average accuracy can be reduced by another 1-2 degrees, then an angle which is in error by more than 10 degrees will not be common. However, users must be aware of the fact that they cannot guarantee (short of measuring the joint angles) that they have achieved an adequate final posture.

Another interesting result of this experiment was that there was very little correlation between the viewing angle of the 3D graphic human form model and the accuracy of the resulting posture. The most probable reason for this was the relatively little variance among subjects. Since most subjects were able to adjust the view angle

adequately, then it is not surprising that the correlation between viewing angle and accuracy is low. However, this does not imply that the viewing angle is unimportant. Part of the reason that the subjects were able to adjust the viewing angle to be correct was because it was emphasized in the training. Perhaps if the viewing angle had not been emphasized, then there would have been a significant correlation due to viewing angle. Further research is necessary to verify that the altering the view angle to match the photograph improves accuracy.

A probable reason that there was not a significant difference in subject preferences for one method over another is because the subjects were nested within methods. This meant that the subjects had to compare the posture entry software to other software that they had used. Considering how difficult many software packages are to use, it is not surprising that all three posture entry methods received fairly high marks. If the subjects had been able to use all three methods then a clear preference for the inverse kinematics methods probably would have been observed simply due to the less posture entry time required to achieve hand positions.

The general perception by the majority of the subjects that the arms were the most difficult part of the body to enter was not surprising considering the degree of freedom at the arms. The subjects who used the inverse kinematics method probably did not find the arms as difficult to enter as the other groups because the inverse kinematics algorithm simplified positioning the arms to achieve the given hand locations.

CHAPTER VIII

EXPERT POSTURE ENTRY METHODS EXPERIMENT

8.1 Introduction

The purpose of this experiment was to compare the accuracy and posture entry time of expert users of the present joint angle posture entry method to the data reported earlier for novice subjects when using the inverse kinematic method. The reason that this study was performed was to demonstrate the advantage of the inverse kinematics method, even for expert users. The results showed that the expert subjects who had experience with the joint angle method were able to match the accuracy but not the posture entry time of the novice subjects using the inverse kinematics method.

8.2 Research hypotheses for expert subjects

In order to test the thesis statement of this research for expert users, the testable hypotheses listed in Table 8.1 were developed.

8.3 Method

The expert subjects followed the same protocol (described in Chapter 6) as the novice subjects. While much of the training was not necessary because of the subjects' experience, the training for the expert subjects was the same as the training for the novice subjects.

All of the five subjects entered postures using the joint angle method, which uses the same joint angles as the 3DSSPP™. No subjects with expertise in the direct manipulation or inverse kinematics methods were available.

TABLE 8.1 *Testable hypotheses for expert subjects experiment*

Posture entry time
Hypothesis 1
Ho: There is no significant difference in posture entry time between expert users of the joint angle method and novice users of the inverse kinematics method.
Ha: There is a significant difference in posture entry time between expert users of the joint angle method and novice users of the inverse kinematics method.
Accuracy
Hypothesis 2
Ho: There is no significant difference in accuracy between expert users of the joint angle method and novice users of the inverse kinematics method.
Ha: There is a significant difference in accuracy between expert users of the joint angle method and novice users of the inverse kinematics method .
Number of manipulations
Hypothesis 3
Ho: There is no significant difference in number of manipulations between expert users of the joint angle method and novice users of the inverse kinematics method
Ha: There is a significant difference in number of manipulations between expert users of the joint angle method and novice users of the inverse kinematics method
Time per manipulation
Hypothesis 4
Ho: There is no significant difference in the time per manipulation between expert users of the joint angle method and novice users of the inverse kinematics method
Ha: There is a significant difference in the time per manipulation between expert users of the joint angle method and novice users of the inverse kinematics method

8.4 Subjects

Five subjects who were experts in ergonomics and the use of the Three Dimensional Static Strength Prediction Program™ participated in the experiment. All subjects were volunteers who were paid $6 per hour for their time. The minimum qualifications to be an expert were; 1) two or more years experience in ergonomics, 2) 40

or more postures described using any method, and 3) 20 or more postures described using the 3DSSPP™. The average qualifications of the five subjects are shown in Table 8.2. Three of the five subjects have described over 100 postures using the 3DSSPP™.

TABLE 8.2 *Average qualifications of the expert joint angle subjects*

Years of experience in ergonomics	5-10 years
Years of experience with computers	3-5 years
Years of experience using computers with a pointing device	3-5 years
Postures described using a categorical method	11-20 postures
Postures described using Keyserling Posture Analysis System	11-20 postures
Postures described using 2DSSPP™	51-100 postures
Postures described using 3DSSPP™	51-100 postures
Average number of postures described per month	3-4 postures

8.5 Results of Expert User Experiment

8.5.1 Accuracy

While the expert joint angle subjects were not able to match the accuracy of the novice inverse kinematics subjects as shown in Table 8.3, the difference was not significant ($F(1,92)=0.214$, $p=0.645$). In addition, there was no difference found in accuracy for hard postures only ($F(1,24)=2.943$, $p=0.099$). The mean accuracy and standard deviation for each part of the body is shown in Table 8.4.

The expert joint angle subjects (8.6°) were more accurate than the novice joint angle subjects (9.3°). The improvement in accuracy, however, was not significant in statistical terms ($F(1,92)=1.7$, $p=0.192$) nor in practical terms.

TABLE 8.3 *Mean and standard deviation differences between entered and measured joint angles (degrees)*

	Posture:	Easy	Medium	Hard	Totals:
Method	Novice Joint angle	6.6 (2.9)	10.2 (2.6)	11.0 (3.7)	9.3 (3.6)
	Expert Joint angle	6.4 (2.0)	9.0 (2.0)	10.4 (2.9)	8.6 (2.8)
	Novice Inverse kinematics	6.8 (2.0)	9.1 (1.9)	8.8 (2.5)	8.2 (2.3)
Totals:		6.6 (2.4)	9.4 (2.4)	10.7 (3.4)	8.9 (3.3)

TABLE 8.4 *Mean and standard deviation accuracy values for the different parts of the body (degrees)*

	Legs	Trunk	Arms
Novice joint angle	3.8(2.9)	6.9(3.9)	12.9(5.7)
Easy	3.6(3.4)	4.3(2.5)	8.9(4.7)
Medium	3.0(1.3)	8.4(3.3)	14.5(4.4)
Hard	4.8(3.4)	8.0(4.5)	15.3(5.8)
Expert joint angle	4.0(2.2)	5.7(3.2)	12.0(4.7)
Easy	3.6(1.6)	4.1(1.6)	8.7(3.4)
Medium	3.5(1.4)	5.4(2.9)	13.0(3.6)
Hard	5.0(3.1)	7.6(3.9)	14.1(5.4)
Novice inverse kinematics	4.2(3.3)	6.4(2.8)	11.0(4.1)
Easy	4.2(2.3)	4.7(1.9)	9.0(3.5)
Medium	3.2(2.8)	6.9(2.3)	12.8(3.3)
Hard	5.3(4.4)	7.6(3.2)	11.1(4.6)

Similar to the novice experiment, an analysis was run to determine the percentage of postures which were within 10° and 15° of the measured joint angles. The results are shown in Table 8.5. The expert joint angle subjects entered a smaller percentage of postures with less than 15° of error than the novice inverse kinematics subjects.

TABLE 8.5 *Percentage of postures with accuracy errors of <10° and <15°*

	<10°			<15°		
Method	Legs	Trunk	Arms	Legs	Trunk	Arms
Expert joint angle	98%	91%	36%	100%	97%	73%
Novice inverse kinematics	94%	87%	43%	98%	100%	84%

A analysis was run to compare the accuracy of the hidden arm versus the accuracy of the visible arm for expert subjects. Similar to the novice experiment, the accuracy for the visible arm was significantly better than the hidden arm. This illustrates that the experience of the experts did not enable them to accurately predict the position of the hidden arm, thus substantiating a further benefit of the inverse kinematics method. The results of the analysis are shown in Table 8.6.

TABLE 8.6 *Comparison of accuracy for hidden arm vs. visible arm for hard postures*

Method	Hidden arm	Visible arm
Expert joint angle	14.4(9.1)	10.4(2.9)
Novice inverse kinematics	10.4(6.1)	11.8(5.9)

8.5.2 Posture entry time

The expert joint angle subjects required significantly more posture entry time (~554 seconds) than the novice inverse kinematics subjects (~338 seconds). Only one of the five expert joint angle subjects was able to match the average posture entry time of the novice inverse kinematics subjects. Table 8.7 compares the posture entry time values for the expert joint angle subjects and the novice inverse kinematics subjects. The expert joint angle subjects required significantly less posture entry time than the novice joint angle subjects. This was the primary advantage of the experience of the experts. The results of the ANOVA analysis are shown in Table 8.8.

TABLE 8.7 *Mean and standard deviation posture entry times (seconds)*

	posture:	Easy	Medium	Hard	Totals:
method	Novice Joint angle	584 (242)	945 (438)	867 (471)	798 (420)
	Expert Joint angle	412 (158)	605 (263)	645 (276)	554 (254)
	Novice inverse kinematics	267 (106)	356 (182)	390 (176)	338 (164)
Totals:		423 (222)	691 (428)	671 (443)	595 (395)

TABLE 8.8 *ANOVA comparison of the mean number of manipulations*

Comparison	DF	DF_{error}	F	p	Significant
Novice inverse kinematics vs. Expert joint angle	1	92	11.2	<0.001	*
Expert joint angle vs. Novice joint angle	1	92	16.5	<0.001	*

The amount of time spent adjusting the view angle for the expert joint angle subjects was relatively small, similar to the novice inverse kinematics subjects. The relative amount of time spent on each task is shown in Figure 8.1.

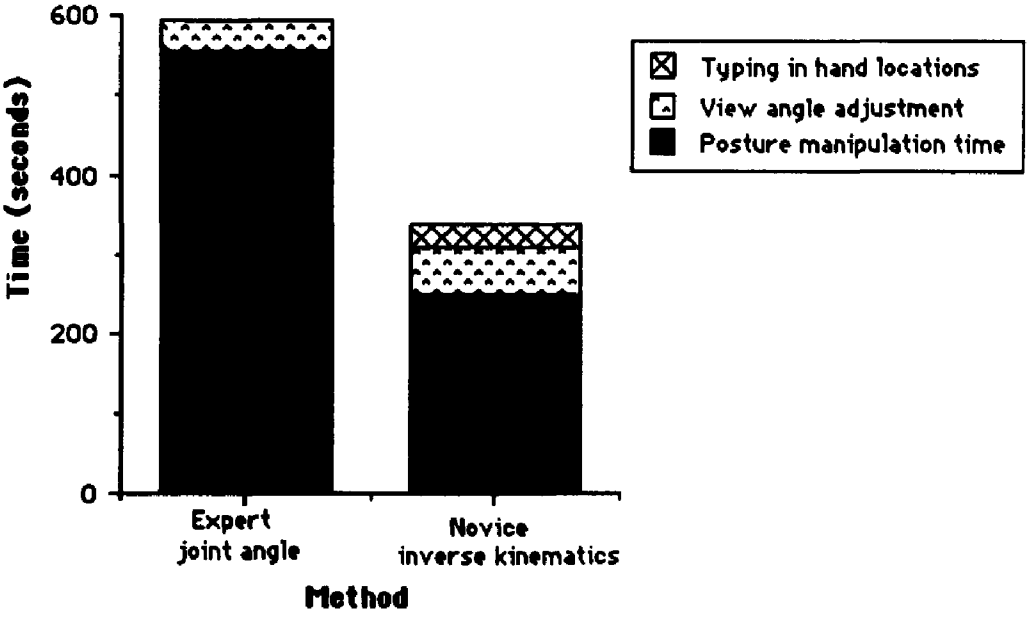


Figure 8.1 *Description of time spent on different tasks while entering postures*

8.5.3 Accuracy as a function of time

The performance of the expert joint angle subjects was modeled using the same nonlinear equation used in Sections 6.7.4.3 and 7.4.3. The values for each of the variables is shown in Table 8.9. The low R^2 values are due to the fact that the accuracy did not show gradual improvement, but rather fluctuated as the subjects attempted to enter the posture. Graphs of the nonlinear equations are shown in Figures 8.2 through 8.4. For comparison purposes, the curves of the novice inverse kinematics subjects are included. Notice that the novice inverse kinematics subjects reach an asymptote much sooner than the expert joint angle subjects for the medium and hard postures.

TABLE 8.9 *Nonlinear models of the expert joint angle subjects performance*

Posture	β_0	β_1	α	R^2
Easy	7.19	13.81	-0.011	0.534
Medium	8.71	24.09	-0.009	0.658
Hard	12.52	22.28	-0.008	0.596

8.5.4 Number of manipulations

The expert joint angle subjects required significantly more posture manipulations than the novice inverse kinematics subjects ($F(1,92)=9.450$, $p=0.003$). Table 8.10 compares the number of manipulations of expert joint angle subjects to novice inverse kinematics subjects. The novice inverse kinematics subjects required fewer mean arm manipulations than the experts (12.8 as compared to 24.3). However, the expert joint angle subjects required fewer mean trunk manipulations (6.9 as compared to 13.1).

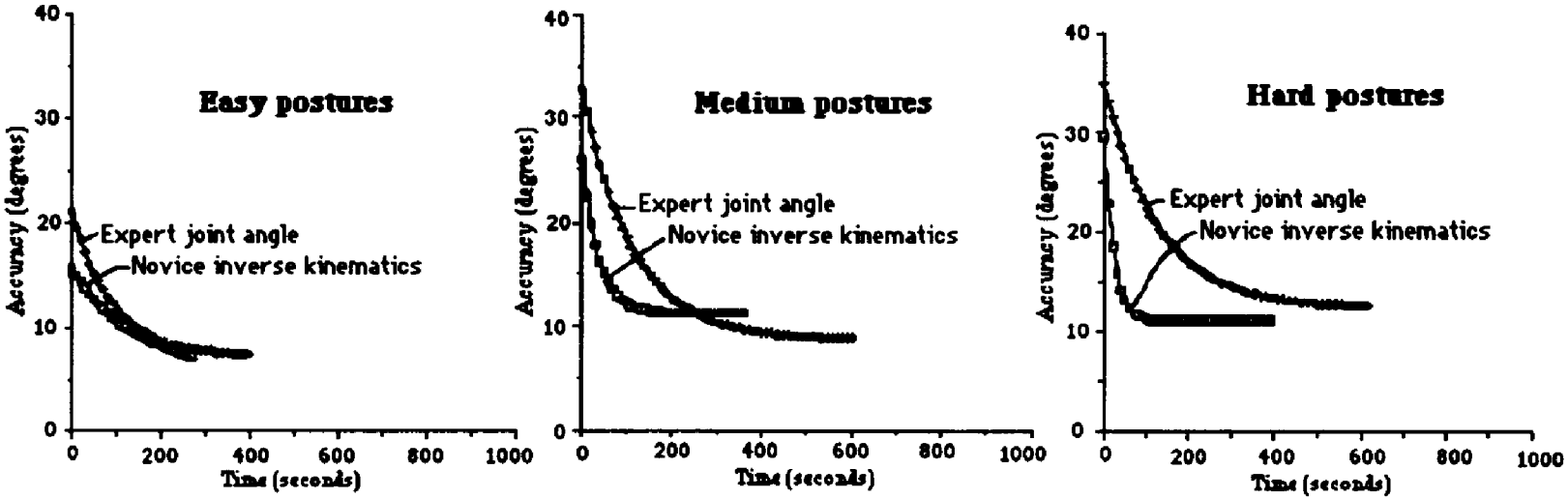


Figure 8.2 Nonlinear models of accuracy as a function of time for expert subjects

TABLE 8.10 *Mean and standard deviation number of manipulations*

	Legs	Trunk	Arms	Total
Expert joint angle	3.7(3.8)	6.9(4.0)	24.3(13.8)	35.0(16.8)
Easy	3.8(2.7)	4.6(1.9)	16.6(7.8)	25.0(7.1)
Medium	4.4(5.7)	8.5(3.9)	25.2(13.3)	38.1(18.5)
Hard	3.0(1.9)	7.7(4.7)	31.1(15.6)	41.9(18.0)
Novice inverse kinematics	3.9(6.9)	13.1(12.0)	12.8(10.2)	29.8(21.8)
Easy	5.3(10.3)	7.0(5.6)	9.0(4.2)	21.3(17.3)
Medium	2.4(3.9)	13.6(10.2)	12.2(10.3)	28.2(19.2)
Hard	4.0(4.8)	18.8(15.4)	17.0(13.0)	39.8(25.0)

8.5.5 Time per manipulation

The amount of time per manipulation was also analyzed. Table 8.11 compares the amount of time per manipulation for expert joint angle subjects and novice inverse kinematics subjects. The difference in time per manipulation between the expert joint angle subjects and the novice inverse kinematics subjects was statistically significant ($F(1,92)=3.980$, $p=0.049$).

TABLE 8.11 *Mean and standard deviation time per manipulation (seconds)*

	Posture:	Easy	Medium	Hard	Totals:
Method	Expert joint angle	16.3 (3.0)	16.6 (5.6)	15.7 (3.0)	16.2 (4.0)
	Novice inverse kinematics	14.7 (4.2)	16.2 (12.4)	10.5 (3.7)	13.8 (9.1)

8.5.6 Training time

The subjects who were expert user of joint angle method received the same training used in the novice experiment, as noted in the Methods section. The expert subjects were able to complete the training faster than the novice inverse kinematics subjects. The primary reason for this result is because the expert subjects already had a good understanding of how to enter postures and hence asked very few questions during the training. A graph which compares the expert joint angle training time to the novice inverse kinematics training time is in Figure 8.3.

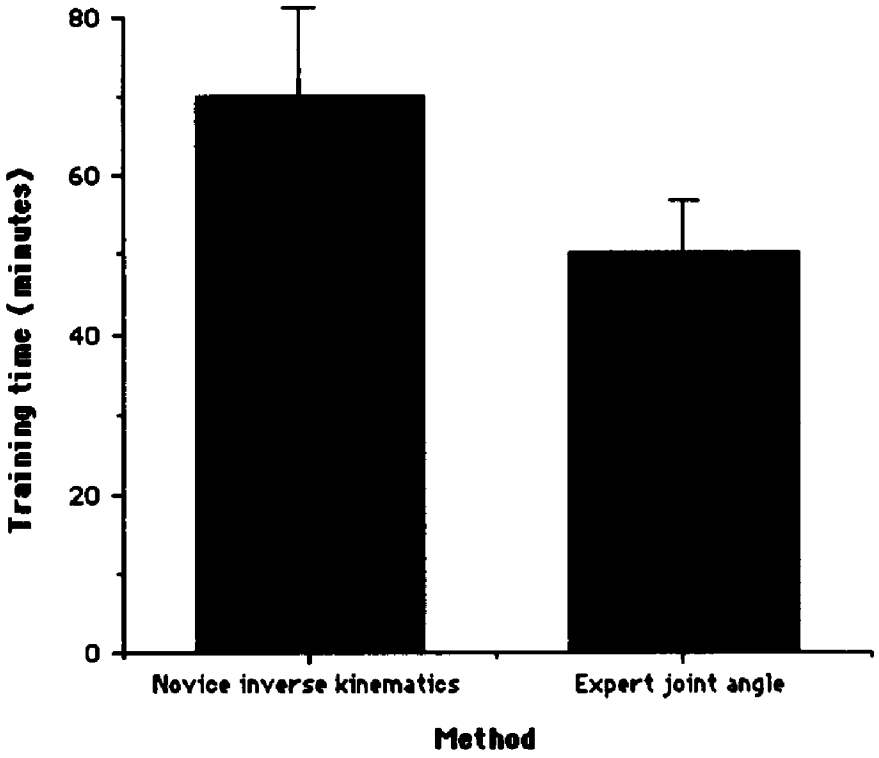


Figure 8.3 *Training time for novice and expert subjects*

8.5.7 Three dimensional graphic human orientation

Similar to the novice experiment, the correlation between accuracy and the orientation of the graphic human model was quite small, -0.127. The correlation between posture entry time and orientation was -0.198. However, as shown in Figure 8.4, the orientations selected by the experts were also quite good. Similar to the novice experiment, the effect of the orientation of the graphic human model cannot be determined because on most trials, the orientations were accurately selected.

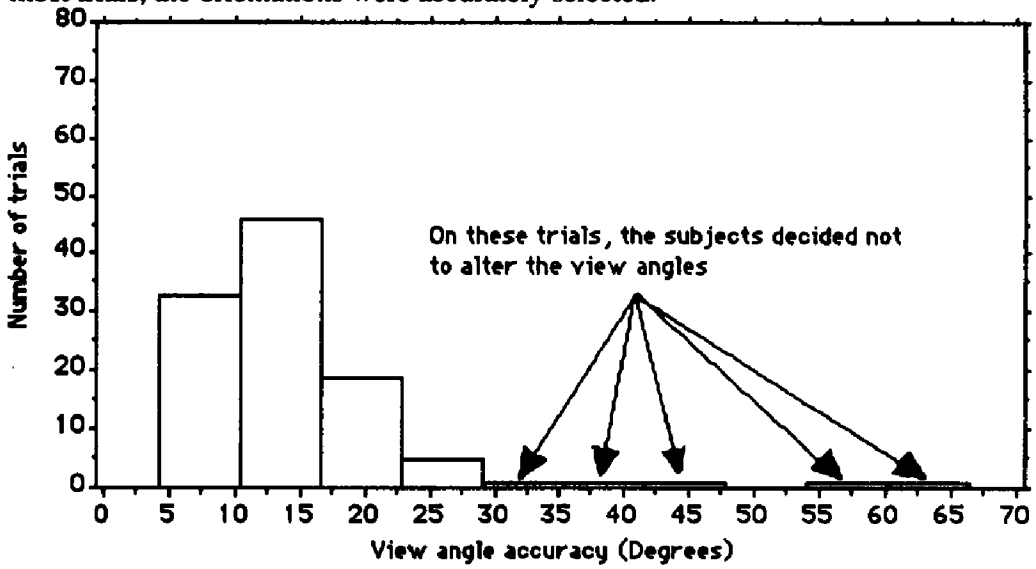


Figure 8.4 *Histogram of expert view angle accuracy data*

8.5.8 Post experimental survey

The five expert joint angle subjects were given a short questionnaire at the conclusion of the experiment. The questionnaire is included in Appendix G.

The first question asked the subjects to compare the ease of use of the software in this experiment to the 3DSSPP™. Four of the subjects rated the experimental software as "easier to use than the 3DSSPP™" and one subject rated the experimental software as "much easier to use than the 3DSSPP™". This demonstrates that the subjects felt that the

differences between the 3DSSPP™ and the experimental software, although minor, were beneficial.

The second question asked the experts which part of the body was the hardest to enter. Three subjects selected the arms and two subjects selected the trunk.

The final question asked the experts to rate the 3DSSPP™ as compared to other software that they use. Three of the subjects rated the 3DSSPP™ to be "harder to use than other software", one subject rated it "much harder to use than other software" and one subject rated it "about the same as other software".

8.5.9 Comparison to NGOMSL analysis

Similar to the novice experiment, a comparison was made to the novice experiment in order to determine the value of the R operator. As stated in Chapter 5, the R operator describes the task of converting a position in three dimensional space into a posture manipulation. Because the average time per manipulation for the expert joint angle subjects was 16.2 seconds and the NGOMSL time per manipulation without R was 4.2 seconds, then the estimated R value for expert joint angle subjects is 12.0 seconds. This is considerably higher than the value for R operator for the novice inverse kinematics subjects which was 8.7 seconds. This demonstrates that even experts were not able to quickly translate three dimensional coordinates into joint angles.

8.5.10 Qualitative feedback

Through informal discussions with the subjects during the rest periods and after the experiment, one subject revealed that he had finalized a hard posture prematurely. Frustration was the reason for his action. The other four subjects did not report that they had experienced any frustration.

In addition, two of the subjects felt that their ability to enter postures would have been enhanced if additional photographs from different views had been available. They also felt that they would like to watch the worker performing the job in order to enhance their ability to visualize the workplace in three dimensions.

8.6 Evaluation of testable hypotheses

The testable hypotheses were evaluated based upon the results reported in Section 8.5. The results are listed in Table 8.12.

TABLE 8.12 *Evaluation of testable hypotheses for expert subjects*

Posture entry time 1. Novice users of the inverse kinematics method require significantly less posture entry time than expert users of the joint angle method
Accuracy 2. There is no significant difference in accuracy between expert users of the joint angle method and novice users of the inverse kinematics method
Number of manipulations 3. Novice users of the inverse kinematics method require significantly fewer posture manipulations than expert users of the joint angle method
Time per manipulation 4. Novice users of the inverse kinematics method require significantly less time per manipulation than expert users of the joint angle method

8.7 Discussion of expert subjects experiment

The performance of the expert subjects provides further evidence that postures are difficult to enter into computers using the joint angle method. Even with experience, users are still forced to use an iterative strategy to enter postures because three dimensional joint angles cannot be easily estimated from photographs.

Another result is that the inverse kinematics method was superior to the joint angle method for expert subjects for the postures used in this research. This is based upon the results that while the expert joint angle method subjects were able to match the accuracy of the novice inverse kinematics method subjects, they required significantly more posture entry time. This means that novice users using the inverse kinematics method will be more efficient than expert users using the joint angle method without a decrease in accuracy. Future research can verify if expert users of the inverse kinematics method are able to improve upon the performance of novices.

As mentioned previously, the primary reason that the novice inverse kinematics subjects were able to enter postures more quickly than the experts was because the inverse kinematics algorithm rapidly predicted good initial postures and always kept the hands in the correct locations. The expert subjects, similar to the novices, were not able to quickly enter a reasonable posture. As shown in Figure 8.4, the experts were able only to slowly converge at what they felt was the correct posture. Another major reason that the expert joint angle subjects were slow was the mental image rotation that the joint angle method required. Even with practice, the experts were not able to quickly translate three dimensional positions into joint angles.

Even though there were no significant differences in accuracy, the result that the novice inverse kinematics subjects were able to match the accuracy of the expert joint angle subjects is important. This result implies that the inverse kinematics algorithm was a great aid to the novices. Even though the inverse kinematics algorithm itself is not extremely accurate, it enabled users with only 70 minutes of training to enter postures as accurately as experts with several years of experience. The reason that the inverse kinematics algorithm is useful is because it is able to predict reasonable postures which provides a good starting posture. It also provides suggestions of postures that the user may not be able to perceive

and reduces the number of possible postures to those in which the hands are in the correct locations. Also, it sets postures of non visible leg or arm.

The expert subjects used in this experiment demonstrated that they were able to enter postures significantly better than the novice joint angle subjects, which is consistent with the Power Law of Practice (Card, Moran and Newell, 1983). This provides evidence that the expert subjects who participated were not unusually poor at entering postures. However, since only a very small population of expert users exist, this hypothesis cannot be tested.

The post experimental survey reveals that most of the expert subjects felt that the joint angle method was difficult to use. In addition, one expert even reported that frustration caused him to finalize a posture prematurely. These results support the hypothesis that the joint angle method is hard to use.

CHAPTER IX

CONCLUSIONS AND FUTURE RESEARCH

9.1 Conclusions

This research tested several different methods of posture entry, both with and without the use of computers. The following conclusions emerged from this study:

1. Users of categorical methods of entering postures, while they are very efficient, frequently make a large number of errors. The primary reason for these errors is because of a lack of spatial feedback about a chosen posture.

2. The use of a three dimensional graphic human form model is a superior means of providing 3D spatial feedback over stick figures. While stick figures aid in the detection of errors, 3D postures can be perceived more quickly by the users if a three dimensional graphic human form model is used.

3. The use of an inverse kinematics algorithm in combination with a direct manipulation interface greatly enhances the ability of novice users to enter postures quickly and accurately for the postures used in this research. Users of the joint angle and direct manipulation posture entry methods are inefficient for all types of postures and inaccurate for hard postures.

4. Expert users of a joint angle method were able to match the accuracy but not the posture entry time of novice inverse kinematics users. This means that a significant advantage of the inverse kinematics method exists even for expert users.

5. Novice inverse kinematics subjects, while not always able to enter postures within the 10 degrees recommended by Chaffin and Erig (1991), were generally quite accurate. The novice subjects of the direct manipulation and joint angles methods were reasonably accurate for easy and medium postures, though they were not sufficiently accurate for hard postures.

Three primary recommendations can be derived from this research;

1. Computerized segmental posture entry methods are prefered over categorical methods because of the ability to provide feedback to reduce the number of errors.

2. Because it improves perception of posture, three dimensional graphic human form models should be included to provide feedback as a part of any computerized posture entry method.

3. Because of the significant improvement in efficiency, an inverse kinematics algorithm is recommended to be included in future posture entry methods. This research has demonstrated the potential benefits of inverse kinematics algorithms as a part of posture entry methods in general. The inverse kinematics algorithm used in this research is not necessarily the correct one to be used, however. There may be postures which it predicts poorly, which could potentially reduce the benefits of inverse kinematics.

9.2 Limitations

A key limitation of this research was that the postures were entered under strictly laboratory conditions. This meant that the subjects were allowed to work as long as they desired to try to enter a posture correctly. However, most analysts have only a limited amount of time in which to spend performing ergonomics analyses. This means that although the analysts may want to enter postures as accurately as possible, they might not be willing to spend as much time per posture as the subjects in this experiment. The inverse kinematics method is still the best posture entry method, however, since the inverse kinematics algorithm quickly predicts a reasonable initial posture.

Another limitation of this research was that the inverse kinematics algorithm was based upon data collected under no load conditions. This may mean that the accuracy of the inverse kinematics algorithm may decrease when predicting heavy load postures.

This research is not directly applicable to cases where posture entry time must be kept to a minimum. For example, methods such as the Posture Analysis System (Keyserling, 1986a) can enter categorical postures in simulated real time. This method is extremely powerful for showing postural variations on a job with a large number of different postures, although analysts must keep in mind that the accuracy of the categories selected cannot always be relied upon to evaluate the biomechanical stress of a specific posture.

9.3 Integration of Results with Previous Research

This research is unique in its focus on the empirical evaluation of specific posture entry methods. However, this research builds upon the previous contributions of others who performed related work. The results of other studies strengthen the conclusions of this research because of the similar conclusions reached.

The research by Kilpatrick (1972) showed that arm and trunk postures could be predicted based upon anthropometry and the hand orientation. Kilpatrick's model was based upon behavioral data and was a fundamental part of the inverse kinematics algorithm described in Chapter 4. Kilpatrick demonstrated the potential for posture prediction as a part of computer-aided man-machine system design.

Park (1973) recognized the importance of postures to the evaluation of manual materials handling jobs and the value of posture prediction. His research also recognized the importance of validating the predicted postures because of the sensitivity of biomechanical stresses to posture. Park found that a simple two dimensional posture prediction model based upon minimization of energy expenditure was able to achieve reasonable approximations of leg and trunk postures. This provided further early evidence that an inverse kinematics algorithm could be useful as a part of a posture entry method.

Keyserling and Budnick (1987) recognized that joint angle methods were difficult for ergonomists to use to enter postures into biomechanical models. Therefore, they proposed a three dimensional digitization method (described in Chapter 3) which would eliminate the need to estimate joint angles to enter postures. Keyserling and Budnick also recognized the importance of collecting empirical data on the ability of ergonomists to use the posture entry method. Their data demonstrated the difficulty of entering postures without the aid of an inverse kinematics algorithm.

Research by Philips (1991) demonstrated that it was feasible to include an inverse kinematics algorithm as a part of a posture entry method. While no empirical testing was performed, the conclusion was reached that an inverse kinematics algorithm was a great asset to posture entry. He also recognized the lack of emphasis on the question of posture entry and its importance to computer animation and ergonomics.

9.4 Future research

The inverse kinematics algorithm used in this research, while it was able to predict postures reasonably well in this experiment, should be the focus of future research. First of all, if a large number of postures representing a large number of different jobs and workers could be measured, then a more valid estimate of the accuracy of the algorithm could be obtained. While the few postures measured in this research gives a rough estimate of the accuracy of the inverse kinematics algorithm, it does not constitute a validation study.

If the accuracy of the inverse kinematics algorithm is not acceptable, then potentially it could be improved to adding more variables to the Snyder, Chaffin, and Schutz (1972) equations, such as force exerted and force direction. A refinement that would make the elbow posture more accurate would be to have more categories of hand orientations other than just prone, semiprone and supine. In short, while the research by Snyder, Chaffin, and Schutz (1972) and Kilpatrick (1970) created a useful inverse kinematics algorithm, further research may improve the model.

Another refinement which could be made to the inverse kinematics model is to add hand and wrist postures. This would be useful in the prevention of carpal tunnel syndrome and other cumulative trauma disorders. Research by Buchholz (1990) could be a good starting point for this research.

Several questions remain about the inverse kinematics posture entry method. The performance of experts is an open question. Can a level of performance be reached such that a 10 degree error at any one joint is rarely observed? Another question is whether a better depiction of the worker and workplace will improve accuracy. The increasing speed and decreasing cost of computers will soon make realistic ray traced images commonplace.

The accuracy of the inverse kinematics algorithm's effect on performance is also unclear. If the inverse kinematics algorithm predicts a posture very poorly, does this have an adverse affect on posture entry time and accuracy? If so, how much? This question is important since it could indicate that additional research into inverse kinematics is necessary before the inverse kinematics posture entry method could be used for all working postures.

Another question that could be answered regarding posture entry is whether two different views of a worker aids the performance of the analyst. A different viewing angle, although sometimes hard to obtain in industry, can reduce the problem of hidden body segments and should aid visualization of the posture. If users are able to utilize information from both photographs, then accuracy should improve. Two of the subjects in the expert experiment felt that additional views would have improved their accuracy.

Another related issue is the effect of a video image as opposed to a static image. A video tape allows the analyst to see the postures which precede and follow the posture of interest. The additional information allows analysts to perceive motion cues which can aid in visualization of the posture.

While the viewing angle of the three dimensional graphic human form model is believed to be important to accurate posture entry, this experiment was not able to prove or disprove this hypothesis. Therefore, further research is necessary. The best way to test the effect of the viewing angle is to have users enter the enter postures using a number of different viewing angles. The three dimension graphic human model viewing angles would include values that match the viewing angle of photographs and others that deviate significantly. The expected result is that the trials in which the viewing angles were correct would result in significantly more accurate postures than those in which the viewing angles were deviated.

Input data that is important to posture entry is the location of the hands. In the posture entry methods experiments the subjects who used the joint angle and direct

manipulation methods were not able to place the hands in the correct locations on the first try. A comparison of the current location of the hands to the correct location of the hands gave the subjects a good indication if additional manipulations were necessary. However, if the correct hand locations were not available, then the subjects may have spent considerably less time entering the posture which would have resulted in significantly worse accuracy. It should be noted that the hand locations are not necessarily simple to obtain, since they must be either measured or estimated from a workstation sketch. A replication of the posture entry methods experiment which did not provide any hand locations would verify that hand location data is vital to accurate posture entry.

APPENDIX A

NGOMSL ANALYSIS OF THE THREE POSTURE ENTRY METHODS

S	M	K	P	H	R	**Direct manipulation method (15 manipulations)**
7	2	2	2	0	0	Accomplish the goal of entering view angles
10	1	2	2	0	1	Accomplish the goal of entering right foot by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering right knee by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering left foot by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering left knee by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering trunk flexion by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering lateral bending by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering axial rotation by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering right elbow in one view by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering right elbow in second view by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering right hand in one view by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering right hand in second view by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering left elbow in one view by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering left elbow in second view by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering left hand in one view by direct manipulation
10	1	2	2	0	1	Accomplish the goal of entering left hand in second view by direct manipulation
1	0	0	0	0	0	Report goal accomplished
151	15	30	30	0	15	106.75

S	M	K	P	H	R	**Inverse kinematics method (hand positions + 10 manipulations)**
7	2	2	2	0	0	Accomplish the goal of entering view angles
19	8	18	1	2	0	Accomplish the goal of entering hand positions
10	1	2	2	0	1	Accomplish the goal of entering right foot by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering left foot by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering hip by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering trunk flexion by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering lateral bending by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering axial rotation by inverse kinematics

10	1	2	2	0	1	Accomplish the goal of entering right elbow in one view by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering right elbow in second view by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering left elbow in one view by inverse kinematics
10	1	2	2	0	1	Accomplish the goal of entering left elbow in second view by inverse kinematics
1	0	0	0	0	0	Report goal accomplished
127	20	40	23	2	10	97

S	M	K	P	H	R	**Keyboard angle entry method (15 manipulations)**
7	2	2	2	0	0	Accomplish the goal of entering view angles
1	0	0	0	1	0	Move hands to keyboard
17	1	4	0	0	1	Accomplish the goal of entering right lower leg angle
17	1	4	0	0	1	Accomplish the goal of entering right upper leg angle
17	1	4	0	0	1	Accomplish the goal of entering left lower leg angle
17	1	4	0	0	1	Accomplish the goal of entering left upper leg angle
17	1	4	0	0	1	Accomplish the goal of entering trunk flexion
17	1	4	0	0	1	Accomplish the goal of entering axial rotation
17	1	4	0	0	1	Accomplish the goal of entering lateral bending
17	1	4	0	0	1	Accomplish the goal of entering right upper arm vertical angle
17	1	4	0	0	1	Accomplish the goal of entering right upper arm horizontal angle
17	1	4	0	0	1	Accomplish the goal of entering right lower arm vertical angle
17	1	4	0	0	1	Accomplish the goal of entering right lower arm horizontal angle
17	1	4	0	0	1	Accomplish the goal of entering left upper arm vertical angle
17	1	4	0	0	1	Accomplish the goal of entering left upper arm horizontal angle
17	1	4	0	0	1	Accomplish the goal of entering left lower arm vertical angle
17	1	4	0	0	1	Accomplish the goal of entering left lower arm horizontal angle
1	0	0	0	0	0	Report goal accomplished
264	17	62	2	1	15	99.31

S	M	K	P	H	R	Method to accomplish the goal of entering the view angles
1						Look at photograph
1	1					Determine vertical view angle
1		1	1			Click on vertical view angle
1						Look at photograph
1	1					Determine horizontal view angle
1		1	1			Click on horizontal view angle
1						Report goal accomplished
7	2	2	2	0	0	6.16

S	M	K	P	H	R	Method to accomplish the goal of entering hand positions
1						Look at photograph
1	1					Determine hand orientation
1			1			Click on hand orientation
1				1		Move hands to keyboard
1						Look at the horizontal position of the left hand

1	1	3				Type in the horizontal position of the left hand and press return
1						Look at the vertical position of the left hand
1	1	3				Type in the vertical position of the left hand and press return
1						Look at the lateral position of the left hand
1	1	3				Type in the lateral position of the left hand and press return
1						Look at the horizontal position of the right hand
1	1	3				Type in the horizontal position of the right hand and press return
1						Look at the vertical position of the right hand
1	1	3				Type in the vertical position of the right hand and press return
1						Look at the lateral position of the right hand
1	1	3				Type in the lateral position of the right hand and press return
1	1					Verify that correct hand positions have been entered
1				1		Move hands to mouse
1						Report goal accomplished
19	8	18	1	2	0	19.64

S	M	K	P	H	R	Method to enter segment position by direct manipulation
1		1	1			Select desired segment in joint menu
1	1					Decide upon desired location of segment in 3D space
1						Retain position of segment in 3D space
1	0	1	1		1	Select position
1						Recall position of segment in 3D space
4	0					Accomplish the goal of verifying that the segment is in the correct position
1						Report goal accomplished
10	1	2	2	0	1	7.11

S	M	K	P	H	R	Method to enter segment position by inverse kinematics
1		1	1			Select desired segment in joint menu
1	1					Decide upon desired location of segment in 3D space
1						Retain position of segment in 3D space
1	0	1	1		1	Select position
1						Recall position of segment in 3D space
4						Accomplish the goal of verifying that the segment is in the correct position
1						Report goal accomplished
10	1	2	2	0	1	7.11

S	M	K	P	H	R	Method to accomplish the goal of entering a joint angle by keyboard entry
1	1					Decide upon position of segment in 3D space
1						Retain desired segment location
1						Retain the type (horizontal or vertical) angle to estimate
4	0	0	0	0	1	Accomplish the goal of estimating angle
4		4				Accomplish the goal of typing in an angle
1						Recall position of segment in 3D space
4						Accomplish the goal of verifying that the segment is in the correct position
1						Report goal accomplished

17	1	4	0	0	1		6.17
S	M	K	P	H	R	Method to accomplish goal of typing in an angle	
1						Recall angle to enter	
1		4				Type in the angle and press return	
1						Verify that angle is correct	
1						Report goal accomplished	
4		4					1.52
S	M	K	P	H	R	Method to accomplish goal of deciding if segment is in desired location	
1						1. Recall desired segment location	
1						2. Look at displayed segment location	
1						3. Decide: if displayed segment location is equivalent to desired segment location then segment location is acceptable else segment location is unacceptable	
1						4. Report goal accomplished	
4							0.4
S	M	K	P	H	R	Method to accomplish goal of estimating an angle	
1						Recall the type of angle (vertical or horizontal) to estimate	
1						Recall desired position of segment	
1					1	Estimate the angle	
1						Report goal accomplished	
4	0	0	0	0	1		0.4

APPENDIX B

BACKGROUND AND POST EXPERIMENT SURVEYS

B.1 Novice subjects background questionaire

1. What is your subject number _____ ?

2. What is your Engineering major or which area of Engineering do you have the most experience? Please circle only one.

Aerospace Engineering	Bioengineering	Chemical Engineering
Civil Engineering	Computer Engineering	Computer Science
Electrical Engineering	Industrial Engineering	Materials Engineering
Mechanical Engineering	Nuclear Engineering	Operations Research

Other (Specify) _____

3. How many (roughly) Engineering courses have you had? Circle one.

None 1-5 5-10 More than 10

4. How many (roughly) non Engineering technical courses have you had? Circle one. (Examples: Chemistry, Physics, Mathematics, etc.)

None 1-5 5-10 More than 10

5. How many years of industrial experience do you have in Engineering? Circle one.

None 1-2 years 3-5 years More than 5 years

6. How many years of experience do you have with computers? Circle one.

None 1-2 years 3-5 years More than 5 years

7. How many years of experience do you have with computers that use some type of pointing device such as a mouse? Circle one.

None 1-2 years 3-5 years More than 5 years

8. How many semesters of Ergonomics courses have you had? (Do not count IOE 333) Circle one.

None 1-2 courses 3-5 courses More than 5 courses

9. How many years of industrial experience do you have in Ergonomics? Circle one.

None 1-2 years 3-5 years More than 5 years

10. Have you ever used a computer system which allows you to enter human posture? Circle one.

Yes No

B.2 Novice subjects post experiment survey

1. What was your subject number? _____

2. How enjoyable was it to enter a posture? (Circle one)

Very enjoyable (like a favorite computer game)
enjoyable
Neutral
Difficult
Very difficult (like the worst software you've used)

3. Which part of the body was the hardest to enter? (Circle one)
Legs
Arms
Trunk

4. If you have any more general comments about entering postures using this method, please write them down here.

_____

_____

_____

_____

_____

_____

B.3 Expert background survey

1. What is your subject number? _____

2. How many years of experience do you have in Ergonomics? Circle one.

None 1-2 2-4 5-10 More than 10 years

3. How many years of experience do you have with computers? Circle one.

None 1-2 2-3 3-5 More than 5 years

4. How many years of experience do you have with computers that use some sort of pointing device such as a mouse? Circle one

None 1-2 2-3 3-5 More than 5 years

5. Approximately how many postures have you described using the following methods (Remember that each job may be composed of several postures):

Pencil and paper (i.e. Armstrong technique, Posture targetting, OWAS, etc.)

None 1-10 11-20 21-50 51-100 More than 100

The Keyserling posture analysis system

None 1-10 11-20 21-50 51-100 More than 100

The 2 Dimensional Static Strength Prediction Program™

None 1-10 11-20 21-50 51-100 More than 100

The 3 Dimensional Static Strength Prediction Program™

None 1-10 11-20 21-50 51-100 More than 100

6. Approximately how many times per month (on the average) do you describe a posture using any of the above methods? Circle one.

Less than one 1-2 3-4 5-10 More than 10

7. If you have ever used the 3 Dimensional Static Strength Prediction Program™, what percentage of the time did you use the direct manipulation input as opposed to simply typing in the angles?

Direct manipulation _____ %

Typed in angles _____ %

B.4 Expert post experiment survey

1. Please rate the software used in this experiment as compared to the 3DSSPP™.

   Much harder to use than the 3DSSPP

   Harder to use than the 3DSSPP

   About the same as the 3DSSPP

   Easier to use than the 3DSSPP

   Much easier to use than the 3DSSPP

2. Which part of the body was the hardest to enter?

   Legs

   Trunk

   Arms

3. Please rate the 3DSSPP as compared to other software that you use.

   Much harder to use than the other software

   Harder to use than the other software

   About the same as the other software

   Easier to use than the other software

   Much easier to use than the software

4. Please write down other comments that you have about the 3DSSPP or the software that you used in this experiment.

_____

_____

_____

_____

_____

_____

_____

_____

APPENDIX C

EXAMPLE POSTURE ENTRY METHODS EXPERIMENT DATA FILE

An example methods data file is shown in Table C.1. Each time the subject pressed the mouse button or typed in a new joint angle the action was recorded and timestamped. The current posture, expressed as joint angles, appears beneath each action.

TABLE C.1 *Example posture entry methods experiment data file*

13:18:51.14 Starting test
-90 90 -90 90 90 90 0 0 -90 90 -90 90 90 90 0 90 0
13:19:30.52 Posture predicted
-42 93 -52 108 84 102 0 0 -48 92 -53 97 84 102 1 61 6
13:19:30.52 Selected right ankle
-42 93 -52 108 84 102 0 0 -48 92 -53 97 84 102 1 61 6
13:19:37.39 Selected left hip
-42 93 -52 108 84 102 0 0 -48 92 -53 97 84 102 1 61 6
13:19:41.96 Altered hip
-43 91 -57 113 90 90 0 0 -48 90 -58 101 90 90 1 63 6
13:20:00.60 Selected trunk flexion
-43 91 -57 113 90 90 0 0 -48 90 -58 101 90 90 1 63 6
13:20:02.68 Altered trunk flexion
-32 83 -64 141 90 90 0 0 -36 82 -71 133 90 90 1 57 6
13:20:11.47 Altered horizontal view -90
-32 83 -64 141 90 90 0 0 -36 82 -71 133 90 90 1 57 6
13:20:53.13 Selected left elbow
-32 83 -64 141 90 90 0 0 -36 82 -71 133 90 90 1 57 6
13:20:57.50 Altered left elbow
-32 83 -64 141 90 90 0 0 -35 84 -73 130 90 90 1 57 6
13:21:06.70 Selected right elbow
-32 83 -64 141 90 90 0 0 -34 95 -78 94 90 90 1 57 6
13:21:10.68 Altered right elbow
-29 92 -72 130 90 90 0 0 -34 95 -78 94 90 90 1 57 6
13:21:12.69 Altered right elbow
-28 98 -75 114 90 90 0 0 -34 95 -78 94 90 90 1 57 6
13:22:50.47 Altered vertical view 12
-28 98 -75 114 90 90 0 0 -34 95 -78 94 90 90 1 57 6
13:23:04.18 Ending test
-28 98 -75 114 90 90 0 0 -34 95 -78 94 90 90 1 57 6

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